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Adams Manufacturing Company, Ltd. Electrical Control of Printing Machinery. 8vo. 64 pp. *Bedford*, 1910
Presented by the Company.

Baeyer, O. von, and **Gehrcke, E.** Über den Zeemaneffekt in schwachen Magnetfeldern. [Reprinted from *Annalen der Physik*, Vol. 29, pp. 941–955.] 8vo. 15 pp. *Leipzig*, 1909
Presented by the Physikalisch-Technische Reichsanstalt.

Baillehache, E. J. le Comte de. Sur la Loi de l'Induction. [Extrait du *Bulletin de la Société Internationale des Électriciens*, 2e Sér., Vol. 10.] 8vo. 28 pp. *Paris*, 1910

——— Recherches sur les Unités Dynamiques du Système Métrique. [Reprinted from *Journal de Physique*, Vol. 9.] 8vo. 7 pp. *Tours*, 1910
Presented by the Author.

Baker, T. T. The Telegraphic Transmission of Photographs. 8vo. 157 pp. *London*, 1910.
Presented by the Author and Messrs. Constable and Co., Ltd.

Barbillion, L., and **Ferroux, G.** Les Compteurs Électriques à Courant Continus et a Courant Alternatifs. 8vo. 233 pp. *Paris*, 1910
Presented by Messrs. Gauthier-Villars.

Bauer, L. A. Biographical Sketch. [Reprinted from *National Cyclopædia of American Biography.*] 8vo. 7 pp. *New York*, 1909

——— United States Magnetic Tables and Magnetic Charts for 1905. (Abstract.) [From *Terrestrial Magnetism and Atmospheric Electricity*, Vol. 14, pp. 41–53.] 8vo. 13 pp. *Baltimore*, 1909
Presented by the Author.

Bauer, Mrs. L. A. The Launching of the *Carnegie*, June 12, 1909. [From *Terrestrial Magnetism and Atmospheric Electricity*, Vol. 14, pp. 135–136.] 8vo. 2 pp. *Baltimore*, 1909
Presented by Dr. L. A. Bauer.

Bedell, F., and **Pierce, C. A.** Direct and Alternating-Current Testing. 8vo. 275 pp. *London*, 1909

Berger, K. Das gleichzeitige Telegraphieren und Fernsprechen und das Mehrfachfernsprechen. [*Telegraphen- und Fernsprech-Technik in Einzeldarstellungen*, Hrsg. von T. Karrass, Vol. 6.] 8vo. 124 pp. *Braunschweig*, 1910

Board of Trade. Memorandum Regarding Details of Construction and Equipment. Fol. 4 pp. *London*, 1910

Presented by the Board of Trade.

Bórns, H. Die Elektrochemie in Jahre 1908. [Reprinted from *Die Chemische Industrie*, Vol. 32, 1909.] 8vo. 182 pp. *Berlin*, 1909

Presented by the Author.

British Fire Prevention Committee. Fire Tests with Fire Extinguishers. Buckets of Water, Hand Pumps, etc., as in common use. 8vo. 16 pp. *London*, 1908

Presented by the Committee.

——— Fire Tests with Fire Extinguishers. Asbestos Cloths, Sand and Steam, as applied to Burning Petrol, etc. 8vo. 24 pp. *London*, 1908

Presented by the Committee.

Brochet, A. La Soude Électrolytique. Théorie Laboratoire Industrie. 8vo. 278 pp. *Paris*, 1909

Brusssels Exhibition, 1910. British Section. Calalogue of Mathematical and Scientific Instruments. 8vo. 240 pp. *London*, 1910

Presented by the National Physical Laboratory.

Cambridge Scientific Instrument Company, Ltd. Duddell Patent Oscillographs. 8vo. 36 pp. *Cambridge*, 1910

Presented by the Company.

Carnegie Institution of Washington. Scope and Organisation of the Institution. 8vo. 32 pp. *Washington*, 1909

Presented by Dr. L. A. Bauer.

——— The Magnetic Survey Yacht *Carnegie* and Her Work. [From *Terrestrial Magnetism and Atmospheric Electricity*, Vol. 14, pp. 57–66.] 8vo. 10 pp. *Baltimore*, 1909

Presented by Dr. L. A. Bauer.

——— Annual Report of the Director of the Department of Terrestrial Magnetism for 1909. [Reprinted from *Year Book*, No. 8, pp. 194–202.] 8vo. 9 pp. *Washington*, 1909

Presented by Dr. L. A. Bauer.

Chree, C. Some Phenomena of Magnetic Disturbances at Kew. (From the *National Physical Laboratory.*) [*Philosophical Transactions of the Royal Society*, Vol. 210, pp. 271–306.] 4to. 36 pp. *London*, 1910

——— The Same (Abstract). [From the *Proceedings of the Royal Society*, Vol. 83, pp. 579–581]. 8vo. 3 pp. *London*, 1910

Presented by the Author.

Churton, T. H. Notes on Alternating Electric Current and Induction Motors. 8vo. 71 pp. *Leeds*, 1910

Presented by the Author.

Collis, A. G. High Tension Switch Gear. [From the *Transactions of the Glasgow Technical College Scientific Society*, Vol. 6, pp. 1–31.] 8vo. 31 pp. *Glasgow*, 1909

Presented by the Author.

Craig, J. The Non-Magnetic Gas Engine of the *Carnegie*. [From *Terrestrial Magnetism and Atmospheric Electricity*, Vol. 14, pp. 131–135.] 8vo. 5 pp. *Baltimore*, 1909

Presented by Dr. L. A. Bauer.

Crouch, L. Tantalum Filament Characteristics. [Reprinted from the *Electrician*, Vol. 64.] 8vo. 7 pp. *London*, 1910

Presented by the Author.

Crudeli, U. Sulla trasformazione del potenziale operate dai trasformatori microtelefonici. [Estratto dall' *Elettricista*, Vol. 9.] 8vo. 1 p. *Roma*, 1910.

Presented by the Author.

Davidge, H. T., and **Hutchinson, R. W.** Technical Electricity. 2nd ed. 8vo. 570 pp. *London*, 1909

Presented by Professor H. T. Davidge.

Deutsche Elektrische Strassenbahnen. Sekundär, Klein- und Pferdebahnen, sowie elektrotechnischen Fabriken, Elektricitätswerke samt Hilfsgeschäften 1909–1910. 13th ed. 8vo. 474 pp. *Berlin*, 1910

Diederichs, H. *See* Güldner, H.

Dike, P. H. An Experimental Investigation of Dip Needle Corrections. [From *Terrestrial Magnetism and Atmospheric Electricity*, Vol. 14, pp. 137–146.] 8vo. 10 pp. *Baltimore*, 1909

Presented by Dr. L. A. Bauer.

Duddell, W. *See* Cambridge Scientific Instrument Company, Ltd.

Ekman, V. W. Über die Schwingungen zweier benachbarten elektrischen Dipole. [From *Arkiv för Matematik*, Vol. 3, No. 23.] 8vo. 32 pp. *Stockholm*, 1907

Engineering Standards Committee. Report on British Standard Copper Conductors. [No, 7, revised.] 2nd ed. Fol. 18 pp. *London*, 1910

Presented by the Committee.

——— Third Report on the Locomotive Committee on Standard Locomotives for Indian Railways. (Incorporating the First and Second Reports, Nos. 5 and 26, revised.) [No. 50.] Fol. *London*, 1910

Presented by the Committee.

Falconnet, H. *See* Seeligmann, T., Torrilhon, G. L., and Falconnet, H.

Ferroux, G. *See* Barbillion, L., and Ferroux, G.

Fleming, J. A., and **Pearson, J. C.** Carnegie Institution Comparisons of Magnetic Standards during 1908. [From *Terrestrial Magnetism and Atmospheric Electricity*, Vol. 14. pp. 3–16.] 8vo. 14 pp. *Baltimore*, 1909

Presented by Dr. L. A. Bauer.

Foster, G. C., and **Porter, A. W.** Elementary Treatise on Electricity and Magnetism. Founded on Joubert's "Traite Élémentaire d'Electricité." 3rd ed. 8vo. 652 pp. *London*, 1909

Presented by Professor G. C. Foster, F.R.S.

Fowle, F. F. The Protection of Railroads from Overhead Transmission Line Crossings. 8vo. 76 pp. *New York*, 1909

Frick, J. Physikalische Technik oder Anleitung zu Experimentalvorträgen sowie zur Selbstherstellung einfacher Demonstrationsapparate. 7e Auflage von O. Lehmann. 2 vols. in four. 8vo. *Braunschweig*, 1904–9

Gati, B. Wechselstrom als Träger von Telephonströmen. [Reprinted from *Elektrotechnische Zeitschrift*, Vol. 30.] 8vo. 2 pp. *Berlin*, 1909

Presented by the Author.

Gehrcke, E. *See* Baeyer, O. von.

——— and **Wogau, M. von**. Magnetische Messungen. (Mitteilung aus der Physikalisch-Technischen Reichsanstalt.) [Reprinted from the *Verhandlungen der Deutschen Physikalischen Gesellschaft*, Vol. 11, pp. 664–681.] 8vo. 18 pp. *Braunschweig*, 1909

Güldner, H. The Design and Construction of Internal-Combustion Engines. A Handbook for Designers and Builders of Gas and Oil Engines. Translated from the 2nd edition, with additions on American Engines, by H. Diederichs. 4to. 691 pp. *London*, 1910

Gumlich, E. Über die Messung hoher Induktionen (Mitteilung aus der Physikalisch-Technischen Reichsanstalt.) Reprinted from *Elektrotechnische Zeitschrift*, Vol. 31.] 8vo. 11 pp. *Berlin*, 1909

Haanel, E. Report on the Investigation of an Electric Shaft Furnace, Domnarfvet, Sweden, etc. 8vo. 38 pp. *Ottawa*, 1909

Presented by the Author.

Hands, A. Lightning Conductors. (The *Electrical Engineer* Reprints, New Series, No. 1.) 8vo. 16 pp. *London*, 1910

Presented by the Author.

Hart, T. Rope Driving, or the Transmission of Power by Ropes. 8vo. 77 pp. *Blackburn* [1910]

Presented by the Author.

Hartz, A. *See* Hersen, C., and Hartz, A.

Heinke, C. Handbuch der Elektrotechnik.

Vol. IX. Elektromotoren, Umformer und elektrischer Motorenantriebe. Von F. Niethammer. 2nd ed. 485 pp. 1910.

4to. *Leipzig*, 1910

Hersen, C., and **Hartz, A.** Die Fernsprechtechnik der Gegenwart (Ohne die Selbstanschluss-Systeme). [*Telegraphen- und Fernsprechtechnik in Einzeldarstellungen*, Hrsg. von. T. Karrass, Vol. 5.] 8vo. 707 pp. *Braunschweig*, 1910

Hirst, H. The Manufacturer and the State (An Address). 8vo. 14 pp. *London*, 1910

Presented by the Author.

Hopkinson, J. Presentation of Marble Bust of the late John Hopkinson to the Institution of Electrical Engineers. [Reprinted from the *Journal of the Institution of Electrical Engineers*, Vol. 44.] 8vo. 8 pp. *London*, 1910

Huggins, Sir W. The Royal Society, or Science in the State and in the Schools. 8vo. 146 pp. *London* [1906]

Presented by the Author.

Hutchinson, R. W. *See* Davidge, H. T., and Hutchinson, R. W.

Karrass, T. *See* Berger, K.

——— *See* Hersen, C., and Hartz, A.

Kempe, H. R. Engineer's Year-Book of Formulæ, Rules, Tables, Data, and Memoranda, for 1910. 17th ed. 8vo. 1,216 pp. *London*, 1910
Presented by the Author.

Le Blanc, M. Die elektromotorischen Kräfte der Polarisation und ihre Messung mit Hilfe des Oszillographen. [*Abhandlungen der Deutschen Bunsen Gesellschaft*, No. 3.] 8vo. 79 pp. *Halle*, 1910

Lehmann, O. *See* Frick, J.

Lindemann, R. Über die Widerstandszunahme unterteilter Leiter bei schnellen Schwingungen. (Mitteilung aus der Physikalisch-Technischen Reichsanstalt.) [From the *Verhandlungen der Deutschen Physikalischen Gesellschaft*, Vol. 11, pp. 682–698.] 8vo. 17 pp. *Braunschweig*, 1909

McIntosh, J. G. *See* Seeligmann, T., Torrilhon, G. L., and Falconnet, H.

Marshall, A. W. Flying Machines, Past, Present, and Future. 3rd ed. 8vo. 135 pp. *London*, 1910
Presented by the Author.

Mason, H. *See* Sheldon, S., and Mason, H.

Murray, T. E. Electric Power Plants. A Description of a Number of Power Stations. 8vo. 350 pp. *New York*, 1910
Presented by the Author.

Niethammer, F. Elektromotoren, Umformer und elektrische Motorantriebe. 2nd ed. *See* Heinke, C., *Handbuch der Elektrotechnik*, Vol. 9.

Nipher, F. E. On the Nature of the Electric Discharge. The One-Fluid and the Two-Fluid Theories. [*Transactions of the Academy of Sciences of St. Louis*, Vol. 19, pp. 1–20.] 8vo. 20 pp. *St. Louis*, 1910
Presented by the Author.

Noad, H. M. Lectures on Electricity, comprising Galvanism, Magnetism, Electro-Magnetism, Magneto- and Thermo-Electricity, and Electro-physiology. 3rd ed. 8vo. 516 pp. *London*, 1849
Presented by A. Marson.

Orlich, E. Kapazität und Induktivität. Ihre Begriffsbestimmung, Berechnung und Messung. [*Elektrotechnik in Einzeldarstellungen*, hrsg. von G. Benischke, Vol. 14.] 8vo. 306 pp. *Braunschweig*, 1909

Ostwald, W. Die Entwicklung der Elektrochemie in gemeinverständlicher Darstellung. 8vo. 211 pp. *Leipzig*, 1910

Oulton, L., and **Wilson, N. J.** Practical Testing of Electrical Machines. 8vo. 215 pp. *London*, 1909
Presented by L. Oulton.

Parliamentary Papers. The Tramways Act, 1870. An Act to Facilitate the Construction and to Regulate the Working of Tramways. 8vo. 35 pp. *London*, 1870

Patchell, W. H. The Electrification of the Ferndale Collieries. [From the *Proceedings of the South Wales Institute of Engineers*, Vol. 26.] 8vo. 111 pp. *Cardiff*, 1910
Presented by the Author.

Pearson, J. C. *See* Fleming, J. A., and Pearson, J. C.

Pedersen, P. O. Über den Empfang Kontinuierlicher, elektromagnetischer Wellen in der Radiotelegraphie. [From *Jahrbuch der drahtlosen Telegraphie*, Vol. 3, pp. 283–294.] 8vo. 12 pp. *Leipzig*, 1910
Presented by the Author.

Pierce, C. A. *See* Bedell, F., and Pierce, C. A.

Phœnix Assurance Company, Ltd. Phœnix Fire Office Rules for the Erection of Lightning Conductors. 8vo. 8 pp. *London*, 1910

Presented by the Company.

Porter, A. W. *See* Foster, G. C., and Porter, A. W.

Post Office Telegraphs. Handbook for Wireless Telegraph Operators working Installations licensed by H.M. Postmaster-General. Revised ed. 8vo. 44 pp. *London*, 1909

Presented by Major W. A. J. O'Meara.

Rasch, E. Das elektrische Bogenlicht, Physikalisch-Technische Grundlagen der Lichterzeugung durch elektrische Entladungsvorgänge. 8vo. 197 pp. *Braunschweig*, 1910

Seeglimann, T., Torrilhon, G. L., and **Falconnet, H.** Indiarubber and Gutta Percha. A Complete Practical Treatise on Indiarubber and Gutta Percha in their Historical, Botanical, Arboricultural, Mechanical, Chemical, and Electrical Aspects. Translated by J. G. McIntosh. 2nd English ed. 8vo. 424 pp. *London*, 1910

Sheldon, S., and **Mason, H.** Dynamo-Electric Machinery. Its Construction, Design, and Operation. Vol. 1., Direct Current Machines. 7th ed. 8vo. 286 pp. *New York*, 1908

Société Internationale des Electriciens. Travaux du Labortoire Centrale d'Électricité. Vol. 1 (1884–1905). 8vo. 514 pp. *Paris*, 1910

Spon, E. & F. N., Ltd. Workshop Receipts for Manufacturers and Scientific Amateurs. New ed. 4 vols. 8vo. *London*, 1909–10

Presented by the Publishers.

Sutton, H. Telephotography. [Reprinted from the *Telegraphic Journal and Electrical Review*, Vol. 27.] 8vo. 3 pp. *London*, 1890

Presented by the Author.

Thornton, W. W. Electricity in Mines. [Reprinted from *Colliery Guardian*, Vol. 99.] 8vo. 16 pp. *London*, 1910

Presented by the *Colliery Guardian* Company, Ltd.

Tissot, C. Les Oscillations Electriques. Principes de la Télégraphie sansfil. 8vo. 464 pp. *Paris*, 1910

Tobler, A. Elektrische Uhren. 2te Auflage bearbeitate. von J. Zacharias. 8vo. 270 pp. *Wien*, 1909

Torrilhon, G. L. *See* Seeligmann, T., Torrilhon, G. L., and Falconnet, H.

Turpain, A. Téléphonie. Du Téléphone Bell aux Multiples Automatiques. Essai sur les Origines et le developpement du Téléphone. 8vo. 186 pp. *Paris*, 1910

Presented by Messrs. Gauthier-Villars.

——— Notions fondamentales sur le Télégraphie envisagée dans son developpement, son état actuel et ses derniers progrès. 8vo. 180 pp. *Paris*, 1910

Presented by Messrs. Gauthier-Villars.

Weingreen, J. Electric Power Plant Engineering. 8vo. 439 pp. *New York*, 1910

Wernicke, K. Die Projektierung und Ausführung elektrischer Licht- und Kraftanlagen. [*Handbuch der Starkstromtechnik*, Vol. 1, Hrsg. von Weigel und K. Wernicke.] 4to. 409 pp. 15 folding plates. *Leipzig*, 1910

Wilson, N. J. *See* Oulton, L., and Wilson, N. J.

Wogau, M. von. *See* Gehrcke, E., and Wogau, M. von.

Young, C. Spons' Architects' and Builders' Price Book, Memoranda, Tables, and Prices. 37th ed. 8vo. 611 pp. *London*, 1910

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OF THE

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Proceedings of the Five Hundred and Second Ordinary General Meeting of the Institution of Electrical Engineers, held in the Rooms of the Institution of Civil Engineers, Great George Street, Westminster, on Thursday, February 10, 1910 — Dr. GISBERT KAPP, President, in the chair.

The minutes of the Ordinary General Meeting held on January 27, 1910, were taken as read, and confirmed.

The list of candidates for election into the Institution was taken as read, and it was ordered that it should be suspended in the Library.

The following list of transfers was announced as having been approved by the Council :—

TRANSFERS.

From the class of Associate Members to that of Members—

John H. Bowden.
Henry P. Clausen.
Robert Foster.
F. W. H. Wheadon.

From the class of Associates to that of Members—

Dudley Stuart,

From the class of Associates to that of Associate Members—

Julian C. Bruce-Kingsmill, Major R.A. (ret.).
William Geo. Perry.

From the class of Students to that of Associate Members—

Alan Bartram.
Thomas O. H. Bates.
Herbert F. H. Blease.
Arthur P. Boden.
Harold Creagh.
Sydney H. Harris.
Arthur L. Hawes.
Joseph Heynssens.
Harold C. Holroyd.
Ralph P. Hulton.
Gerald Jacques.
Robert Livingstone.
Harold Mackay.
Thomas Mason.
Edward B. Percival.
Edward A. Powell.
William James Procter.
Joseph R. Robinson.
Leo Romero.
Addison B. Smith.
Geo. K. Tweedy.
Egerton J. Ward.
Bruce G. White.
Reginald C. C. Yates.

From the class of Students to that of Associates—

Alfred P. Chalkley.
Louis F. R. Lewin.

Messrs. B. B. Heaviside and H. Brazil were appointed scrutineers of the ballot for the election of new members, and, at the end of the meeting, the following were declared to have been duly elected :—

ELECTIONS.

As Member.

Raymond S. Kelsch.

As Associate Members.

Percy Frederick Allan.
James William Barber.
Edward Albert Behrens.
Cuthbert Wm. Bentley.
Alexander Charles Borthwick.
George Frederick Boxall.
Leonard Harvey Combe.
Hugh Denehy.
Frederick William Foster.
Percy Sheldon Glover.
Frank Hallows.
Alexander Ireland Hodgson.
John Francis Luscombe.
William David McLaren.
David Macfarlane Macleod.
Charles George M. New.
Leonard W. Schuster, B.A.
Waring S. Sholl.
John Walter Sims.
Aage Sören M. Sörensen,
Percy Leonard Weston.

As Associates.

Thomas Thorne Baker.
Stanley Rudd,
William Bedford Smith,

As Students.

Major Frederick Allsop.
Joseph Peter Annacker.
George Hugh D. Ascoli.
Wyndham Ewen Barker.
Lionel Edward Barnard.
Arthur Stephen M. Best.
James M. Bloomfield.
Cyril Percy Bowmaker.
Ernest Alexander Boyd.
Claude Clifford H. Brazier.
Charles Arnold Brearley.
Robert Bagot Breeze.
Roland Hugh P. Broome.
Charles Lester Bullock.
Ernest William N. Burden.
Harry Gustav Byng.
Hubert Carey-Thomas.
Leslie Walter Chambers.
William James Chambers.
Thomas Arthur Collett.
Russell Ernest Connold.
Leslie William Cooper.
Watson Edward Cornille.
Philip Ray Coursey.
Harold Henry Unite Cross.
William Boston Cushion.
David Batatha Da Cunha.
Arthur Thomas P. Davies.
George Faraday Davies.
Mario de Angelis.
Harlanyo G. de Coundouroff.
Lancelot Brown Dent.
Roderick World Dudley.
Henry Montgomery Dunkerley.
Robert Chapman Dunn.
Charles Thomas Eaddy.
Harry John Eley.
John William Elliott.
Edmund Lashley M. Emtage.
Alfred William Epton.
Robert Arthur Everitt.
Alfred Mortland Faulkner.
Hugh Herbert Foster.
James A. Garbarino.
Albert Hardy Gay.
David Gill.
Harold Green.
Harry Greenwood.
Guy Baldwin Hay.
Percy Victor Henk.
James Edward Hogarth.
Gilbert Holdsworth.
Charles Louis Huang.
Reginald Northcott James.
Vinayak Ganesh Kirloskar.
Frederick Robert L'Estrange.
William Henry Lovell.
Roderic William Macklin.
Matthew Marshall.
John Bernard Miller.
Theodore D. Morison.
Dudley Eric Nicolle.
Kendrick Northover.
Eugene Orloff.
John Davidson Peattie.
Nelson Joseph Perryman.
David Auslau James Petruse.
Frederick Charles L. Racker.
Stuart Milner Rawson.
Stanley Whitlock Redclift.
Alexander Riddle.
Leslie Roberts.
William Ewart Russell.
John Allen Rutherford.
Percy George Ryder.
Christian Stephen Salvesen.
Charles Wallace Saunders.
Gilbert James Scott.
Vasco Davidson G. Serodio.
Sriram Venkatasubba Setti.
Eric William Sleight.
Bartholomew Snowball.
Vivian Soper.
William Gordon Spencer.
Stanley Edward W. Taylor.
John McLaren Thornton.
Florentin Troutet.
Charles Croswaithe Villa.
John Guy Lawson Welch.
Albert Willmore.
Edward Hamilton E. Woodward.
Reginald Pardoe Yates.

Donations to the *Building Fund* were announced as having been received since the last meeting from R. H. Burnham, R. A. Dawbarn, F. Gill, S. E. Glendenning, Colonel H. S. Hassard, and A. von Siemens; and to the *Benevolent Fund* from V. K. Cornish, B. Davies, H. C. Donovan, E. Fawssett, F. Gill, F. E. Gripper, H. G. Harris, C. C. Hawkins, K. Hedges, S. Insull, E. S. Jacob, Dr. G. Kapp, J. P. Lawrence, A. E. Levin, W. M. Mordey, Hon. C. A. Parsons, A. H. Preece, W. Ll. Preece, T. Rich, R. Robertson, A. J. Stubbs, W. C. P. Tapper, F. J. Thompson, and A. P. Trotter, to whom the thanks of the meeting were duly accorded.

The following paper, "Losses off Transmission Lines due to Brush Discharge with Special Reference to the Case of Direct Current," by E. A. Watson, M.Sc. (Eng.), Student, was read and discussed (see page 5).

LOSSES OFF TRANSMISSION LINES DUE TO BRUSH DISCHARGE, WITH SPECIAL REFERENCE TO THE CASE OF DIRECT CURRENT.

By E. A. WATSON, M.Sc. (Eng.), Student.

(*Paper received August* 13, 1909, *and read in London on February* 10, 1910.)

SYNOPSIS.

General Considerations.
Previous Work on the Subject.
Comparison of Results of Previous Experimenters.
Mechanism of the Loss.
Experiments conducted by the Author on Losses off Wires under Direct-current Pressures.
Consideration of Results of Experiments.
Conclusions arrived at.

Leaving aside economical considerations, there are three factors which may be said to limit the voltage which can be employed on a transmission line. These are—

1. The generating or transforming apparatus.
2. The line insulators.
3. Brush discharge off the line itself.

Of these it may safely be said that the third is the only one which will ultimately need to be considered, and is, at the present time, of considerable importance. The limits imposed by (1) and (2) are chiefly a matter of design, requiring, of course, a large amount of experience, but none the less capable of considerable expansion above the values at present customary.

The use of oil insulation for transformers and switches, the introduction of "condenser-type" terminals for bringing out leads from apparatus, and the new and rapidly growing use of "suspension-type" insulators for the overhead line, seem to indicate that on neither of these scores is it possible to say that any definite voltage has been reached beyond which it is impossible to go.

With the third factor, however, it seems to be otherwise, and since it is beyond our power to increase the insulating power of air, unless there takes place a considerable change in the present practice of line

construction, there will always be some voltage limit which it is not possible to exceed. It is proposed to consider this question in detail.

General Remarks on the Subject.

The question as to whether a discharge will take place off a wire or not seems to depend upon the value of the electric stress in the immediate neighbourhood of the wire. If this stress should exceed the electric strength of the air in which the wire is immersed a discharge will occur. If the wire is sufficiently close to the other boundary of the field of force which produces the stress the discharge will be actually disruptive, such as is given by a spark or arc; in the case of a transmission wire, however, this is not the case, and the discharge takes the form of a luminous envelope surrounding the wire, and is generally known as the corona. It produces a slight noise, and although only faintly luminous to the eye, gives off a powerfully actinic light, and can be readily photographed.

In the following formulæ let—

R represent the electric stress in kilovolts per centimetre.
a represent the radius of the wires in centimetres.
d represent the distance apart of the centres of the wires in centimetres.
h represent the height of the wires above the earth.

Then for two parallel wires indefinitely far from the earth we have—

Maximum value of R at surface of wire—

$$= \frac{V}{2\,a \log_e \frac{d}{a}} \left(1 + \frac{a}{d}\right)^2 \text{ very nearly,}$$

where V is the voltage between the wires.

For one wire and earth we have—

$$R_{max.} = \frac{V}{a \log_e \frac{2h}{a}} \left(1 + \frac{a}{2h}\right)^2 \text{ very nearly,}$$

where V is the potential of the wire above earth.

For two wires not indefinitely far from the earth we have—

$$R_{max.} = \frac{V}{2\,a \log_e \frac{d}{a} \dfrac{1}{\sqrt{1 + \left(\frac{d}{2h}\right)^2}}} \left(1 + \frac{a}{d}\right)^2 \text{ very nearly,}$$

where $+\frac{V}{2}$ and $-\frac{V}{2}$ are the wire potentials relatively to the earth.

For a 3-phase line arranged in the customary manner at the three corners of an equilateral triangle we have—

$$R_{max.} = \frac{V}{a \log_e \frac{d}{a}\left[1 + \left(\frac{d}{2h}\right)^2\right]^{-\frac{1}{2}}}\left[1 + \frac{\sqrt{3}}{2}\frac{a}{d}\right]^2 \text{ very nearly,}$$

where V is the star voltage of the system.

These formulæ, it should be noted, are only strictly applicable when a is small compared to d—*i.e.*, as in the case of an ordinary transmission line. For any such case the error involved is less than 1 per cent, so that it is hardly necessary to consider the exact forms which they should take. These will be found in various papers by Dr. Russell.*

For a wire in a concentric cylinder we have exactly—

$$R_{max.} = \frac{V}{a \log^e \frac{b}{a}}.$$

where V is the potential difference between wire and cylinder, and b the radius of the cylinder.

As soon as the corona forms it is a well-established fact that a large loss of energy will occur. It is therefore of importance to determine the value of the electric stress at which a corona will form and the effect of various conditions upon the value of this stress.

Previous Work upon the Subject of the Corona.

Most of the work so far accomplished has been done in the United States, where the long distances and high voltages prevalent have emphasized the need for accurate knowledge of the subject. Some of the earliest tests were those made at Pittsburg by Mr. C. F. Scott, and at Telluride by Messrs. Scott and Mershon, the Telluride ones being carried out on an actual line in Colorado at a very considerable altitude.

Professor Ryan, of Cornell (now of Stanford) University, then took the matter up; he analysed the results obtained by Messrs. Scott and Mershon, and also carried out various experiments to find the influence of pressure and temperature and also of the presence of water vapour upon the point of formation.

Experiments have also been carried out by Professor H. B. Smith, at Worcester (Mass.), and by Signor Jona in Italy. The most recent tests, however, are those made by Mr. R. D. Mershon, on a high-tension line, 1,000 ft. long, at Niagara Falls, experiments being conducted on a large number of sizes of conductor, both plain and stranded under different conditions. All these tests were made with alternating currents, and while agreeing in some respects yet have many points of divergence.

* *Proceedings of the Physical Society*, vol. xx., p. 73, and in his book on "Alternating Currents."

The method of test and means of observation employed differed considerably, and it is possible that this may have some bearing on the discrepancies between the various observers. Thus the critical point in the Telluride measurements was obtained by taking readings of loss both on the actual line and on a so-called dummy line having the same number of insulators as the experimental one without the wire in between (that is, they were placed in a group close together). Subtracting the loss on the dummy line from that on the experimental one a curve of loss was obtained from which the critical point was deduced.

In Professor Ryan's tests, on the other hand, use was made of

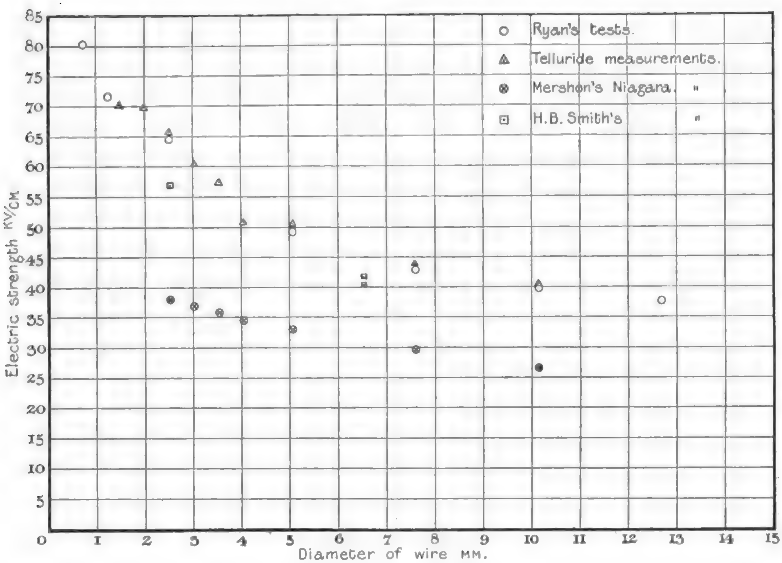

FIG. 1.—Comparison of different Experimental Results.

the visibility of the corona in order to determine the critical point. The wire was viewed in a dark room and the voltage at which the wire appeared luminous was noted.

Mershon's later tests were made by supporting the wires from paraffined cords hung from insulators. The loss over these cords being negligible, the true atmospheric loss could be read immediately. Readings of power lost were made on the low-tension side of the transformer employed, a special arrangement being used to allow automatically for the iron losses.

Some of the figures obtained by different experimenters are given in Fig. 1. Two things will be noticeable from them: first, that they roughly fall into two groups comprising on the one hand the Telluride tests and Ryan's experiments, and on the other, Mershon's Niagara

results, which give values considerably lower than any of the others; secondly, that none of the tests give a constant value for the electric strength (which theory would have us expect), but one which is greatest for the small wires and decreases rapidly at first as the wire size is increased, eventually tending, however, to a steady value for wires of 10 mm. diameter and over.

The large discrepancy between Mershon's Niagara results and the others is probably due to several causes. These will be treated more fully later; they may be put down as—

1. Mershon's method of deducing the critical point (see Fig. 2) probably gives lower values than the method of producing the curve of loss back to the line of zero loss or observing the point at which luminosity commences.

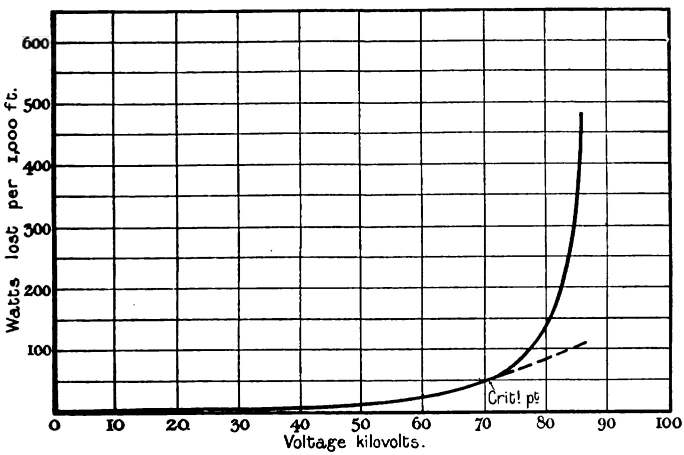

FIG. 2.—Showing Mershon's Method of Deducing the Critical Point.

2. Mershon's tests were made under actual conditions in an atmosphere not specially pure or free from smoke and floating particles, whereas Ryan's tests were made under artificial laboratory conditions and the Telluride ones were taken at a great altitude in the mountains where the atmosphere was probably exceptionally clean and free from floating impurities. It is known that the cleanness of the wire has a bearing upon the critical point, and it is probable that part of the explanation of the discrepancy should be sought here. For any line working under normal conditions in this country it would seem to be advisable not to allow the electric stress to exceed the values obtained from Mershon's experiments. If the other figures are to be used a factor of safety ought to be allowed.

Mechanism of the Loss.

The exact manner in which the loss occurs cannot be said to be clearly understood. Some writers appear to think that the loss is due to the ohmic resistance offered by the corona to the capacity current flowing to its outer boundary. When a wire is enveloped in a corona, there appear to be some grounds for the belief that its outside boundary acts as if it were the surface of the wire and forms the termination of the lines of force which permeate the surrounding medium, so that the charging current of the line would have to cross the corona and reach its outer surface.

This will involve the continuous existence of the corona even during the periods when the voltage of the line is of zero value, and as to this practically nothing is known; it appears just possible, however, that the interval given between successive maxima of the voltage wave is not sufficient for the disrupted air to heal itself again.

The estimation of the loss will involve a knowledge of the size of the corona. It is stated by Jona that if a luminous wire be viewed in a dark room the diameter of the corona visible is the same as that of the wire for which the voltage applied would just not suffice to produce loss. Thus, if a small wire were surrounded by a corona 10 mm. diameter, the voltage required would be the same as the critical voltage for a wire 10 mm. diameter.

On this assumption it is easy to predict the diameter of the corona which will be produced by any given impressed voltage.

It is, however, rather doubtful whether the preceding is strictly accurate. It should be so were the electric strength of air a constant, but there seems every reason to believe that this is not so, but that it is much greater near the surfaces of conductors than it is in bulk. This being so, the corona diameter will, in general, be greater than the diameter of the corresponding wire for which the voltage considered is the critical one.

If a curve connecting electric strength of air with distance from the surface of the metal be available, and it may be obtained in a manner shown later in the paper, a closer approximation may be made by plotting the value of the electric stress against the distance measured from surface of conductor. This will give a curve cutting the curve of electric strength of the air at a point which determines the corona diameter.

Before breakdown the stress at a point at a distance r from the centre of one of a pair of wires of radius a at a distance d apart and indefinitely far from the earth will be given by—

$$R = \frac{V}{2\log\frac{d}{a}}\left(\frac{1}{r-\frac{a^2}{d}} - \frac{1}{d-r}\right) \text{ very nearly.}$$

After breakdown, however, this no longer holds, and we have three alternatives to consider :—

1. The wire potential is conveyed to the outer boundary of the corona without any appreciable voltage-drop when the stress will be—

$$R = \frac{V}{2r\log\frac{d}{r}}\left(1+\frac{r}{d}\right)^2.$$

2. The potential at the corona boundary is less than that of the wire by some quantity equivalent to a resistance drop and possibly of the value of, but certainly not greater than—

   Mean electric strength $\times$ thickness of corona.

   Then we have—

$$R = \frac{V - R_{max.}(r-a)}{2r\log\frac{d}{r}}\left(1+\frac{r}{d}\right)^2.$$

3. Something intermediate between 1 and 2.

Having found the corona diameter, there yet remains to be found what the loss in it is.

Obviously if assumption No. 1 held, the loss would be zero, as the charging current would meet with no resistance.

Also if (2) held, there would be no loss, as all the charge could be carried by the wire and outside surface of the corona acting as the two coatings of a condenser.

The loss will be a maximum when a condition half-way between (1) and (2) obtains and the loss will then be equal to $\frac{1}{\sqrt{2}}$ times the charging current of the corona multiplied by the voltage drops across it. (The current flowing conductively through the corona is out of phase with that crossing it by its condenser action.) To check this an example may be taken from Mershon's paper. A pair of wires 2·60 mm. diameter at 140 cm.-centres, had a voltage of 96·2 maximum kilovolts impressed upon them. The loss was 1,500 watts per kilometre at 73 cycles per second. If this is worked out it is found that the corona thickness is 0·8 mm. and its diameter therefore = 4·2 mm., the loss per kilometre of line (2 wires) coming out to 0·364 k.w.

This is the maximum possible on the assumption made, but it is seen to be less than one quarter of that actually occurring.

It has been derived on the assumption that the corona exists continuously. Let us now suppose it to be reformed at each alternation of the voltage wave. As the voltage rises, there comes a point where the layers of air next the conductor are stressed beyond their electric strength and break down. As the voltage rises still more, further layers are disrupted and a corona is formed whose size depends upon the value which the maximum point of the wave attains.

Each elemental shell of air just before breakdown has a certain amount of energy stored up in it which on disruption is converted into heat, thus giving rise to the loss which occurs.

The energy stored in unit volume of air under electric stress R is—

$$\frac{R^2}{2}\,\frac{1}{4\pi} \text{ ergs when R is in electrostatic units.}$$

(1 Electrostatic unit = 300 volts/cm.)

The energy stored in an elemental tube of the corona will be—

$$\frac{R^2}{2}\,\frac{1}{4\pi} \times 2\pi r\,\delta r \text{ ergs per cm. length of wire.}$$

$$= \frac{R^2}{4}\, r\,\delta r.$$

$$= \frac{11{\cdot}1\, R^2}{4}\, r\,\delta r, \text{ where R is in k.v./cm.}$$

The total power lost in the formation of the corona reduces to—

$$0{\cdot}0556 \sim \int_{a_0}^{a_1} R^2\, r\,\delta r. \text{ watts per kilometre.}$$

where a_0 is the radius of the wire and a_1 that of the corona.

Applying this to the case just considered and integrating the expression graphically by means of a curve connecting R and the distance from the surface of the wire, we obtain a loss of 254 watts per kilometre of double line.

This also is very much less than that actually observed, and we are forced to conclude that there must be some other source of loss in addition to the foregoing.

This conclusion is strengthened if we consider the case of a direct-current line. Both of the arguments so far employed, if extended to cover the direct-current case, would imply that the loss under steady pressure should be zero no matter what the voltage of the line is. This is, of course, directly contrary to all experience, as it is well known that visible brush discharge will occur from direct-current apparatus if the voltage is too high. The question that arises is, How are these losses produced and to what are they due?

It was at first thought that it would be possible to explain the direct-current loss on the basis of the mechanical forces exerted on the layers of disrupted air surrounding the wire, imagining the charge to be transferred from the wire itself to the layers of air. The so-called electrostatic pressure acting on this air due to the charges would then cause it to move outwards and away from the wire. Fresh air would come up and take its place to be broken down in turn, and so a constant loss of energy would occur equal to the volume of air passing

the wire multiplied by the energy stored in unit volume at breakdown. Support was lent to this theory by the fact that the brush discharge from a point is always accompanied by a noticeable wind, although it was not quite clear in the case of a wire how the fresh air was going to get in to take the place of that which had been driven away.

The pressure (force per cm.²) acting on the disrupted air will be $\frac{B^2}{8\pi}$ dynes/cm.², where B is the electrostatic flux density at breakdown, *i.e.*, the potential gradient; assuming free access of air to take the place of that driven away we obtain—

$$\frac{\rho v^2}{2} = \frac{B^2}{8\pi}$$

(ρ = density of air, v = velocity of air),

$$v = \frac{B}{\sqrt{4\pi\rho}},$$

which works out at $v = 7{\cdot}84$ B.

Converting to k.v./cm. we obtain—

$$v = 26{\cdot}1 \text{ R cms./sec.}$$

For a value of R = 40 k.v./cms. this gives a velocity of about 10 metres per second.

Power lost per cm.² of surface—

$$= v\frac{B^2}{8\pi} \text{ ergs. per second,}$$

$$= 1{\cdot}153 \left(\frac{R}{100}\right)^3 \text{ watts.}$$

Although this formula appears in certain cases to give results of the right order of magnitude, the assumptions on which it is founded are probably not correct, and the breakdown which actually takes place is not a uniform one of the whole body of air.

Considerable light has been thrown on the subject by the work of Righi and other experimenters on the discharge from steadily electrified points.

They have shown that when a point is electrified to such a potential as to cause a brush discharge to take place, a stream of gaseous ions is projected from it whose velocity may be readily measured, and is of the order of 1·5 cm. per second for a field of 1 volt per cm.—*i.e.*, much greater than is given by the formula which has just been developed. It seems, therefore, that when a direct-current brush discharge occurs the charge is not carried by the whole of the air which is in contact with the charged body, but by certain agglomerations of molecules which are driven off at a speed about fifty times as great as that with which the air as a whole would move. These

charge carriers under certain circumstances drive the main body with them, forming the so-called electrical wind, but this wind is the effect rather than the cause of the loss of electricity from the conductor. It is believed also that in the case of an alternating-current corona most of the loss is due to this cause, and only a small amount to the energy stored in the broken-down air film or its resistance to the charging current flowing to its outer boundary.

Experiments Carried Out.—The foregoing is intended to give a brief account of our present knowledge upon the subject. It is now proposed to give an account of some experiments made by the author upon the loss off wires under direct-current pressures and with different conditions, special attention being paid to the effect of variations of atmospheric pressure.

These experiments were carried out at the Electrical Engineering Laboratories of the University of Liverpool during the months of May, June, and July, 1909.

Although the question of losses off direct-current transmission lines is not of such immediate importance as the corresponding case for alternating currents, it is yet of considerable interest in view of the extensive adoption of high-tension direct-current transmission in France and Switzerland and its advocacy for the proposed transmission from Victoria Falls to the Rand.

Experiments were made upon—

1. A wire in a concentric cylinder.
2. Two wires stretched parallel out of doors.

It was intended to use (1) as the principal source of information in the tests and employ (2) chiefly as a check upon the deductions made from (1), and also to determine what factor of safety ought to be allowed in an actual transmission line upon the figures obtained by the tests on the wire and cylinder.

The use of a wire in a concentric cylinder was decided upon for the following reasons :—

1. The distribution of flux is subject to easy mathematical calculation, and is uniform all round the wire.
2. A lower voltage is required than is the case for two parallel wires (less than half, in fact).
3. The conditions of pressure, temperature, and humidity can be varied at will.

Method of Test on Wire in Cylinder.

The wire was mounted at the centre of a cylinder of galvanised iron 6 ft. long and 8 in. diameter. The ends were flanged and closed by cast-iron covers, and the pressure could be reduced to 350 mm. of mercury by means of a small motor-driven pump, fitted with automatic control so as to keep the pressure in the cylinder constant at any required value. The degree of humidity could also be

varied by drawing in air either through drying agents such as calcium chloride or through masses of cotton waste well soaked in water.

Ebonite terminals were arranged in the ends, that at one merely supporting the end of the wire, that at the other serving to bring it out and make connection with it. In order to guard against any leakage occurring in the latter terminal, the wire passing through was protected by a concentric metal tube at the same potential so connected that the current supplying it was not passed through the microammeter which measured the leakage off the wire.

The general arrangement of the connections employed is shown in Fig. 3.

Current was supplied by a special form of influence machine (Fig. 4) of large output driven by an electric motor, the machine being capable of working up to 70,000 volts. In order to have control over the output it was arranged to be separately excited from an ordinary two-plate Wimshurst machine.

Across the terminals of the "exciter" was connected a compressed air-insulated voltmeter and a needle-point "spark-gap." The brush discharge from the points of the gap kept the excitation voltage down to any required figure, and by sliding the electrodes in or out any desired output could be obtained from the main machine.

Across the terminals of the main generator was connected a condenser which served to keep the terminal voltage steady, and in the leads between the machine and apparatus resistances and inductances were arranged as shown in the diagram, the object of which was to prevent the existence of any voltage oscillations on the apparatus itself.

A 100,000-volt compressed-air voltmeter was connected across the apparatus, and a reflecting microammeter enclosed in a potential screen and mounted on a 75,000-volt insulator was placed in the lead to the wire under test, and as near to the end of the wire as possible. All connections were made of ⅜-in. brass tubing in order to avoid brush discharges.

In the tests on the parallel wires a similar arrangement was adopted, the leakage over the insulators being collected and measured, and another voltmeter was employed connected between one wire and earth in order to insure that the two wires were equally positively and negatively charged.

In order to obtain higher pressures than could be given by the one machine a 4-plate 4-pole Wimshurst (giving the same current as an ordinary 8-plate machine) was arranged so that it could be put in series with the main generator.

The wires employed in the tests were 12 metres long, and were stretched at a distance of 1 metre centre to centre.

Appearance of Discharge.

As is to be expected there is considerable difference between the behaviour of the wire when positively and when negatively electrified. When the wire was positive under certain conditions, if

viewed in a dark room, the space surrounding it for a distance of 1 or 2 cms. was full of fine branching bluish purple brushes darting about continually and never remaining stationary at one spot.

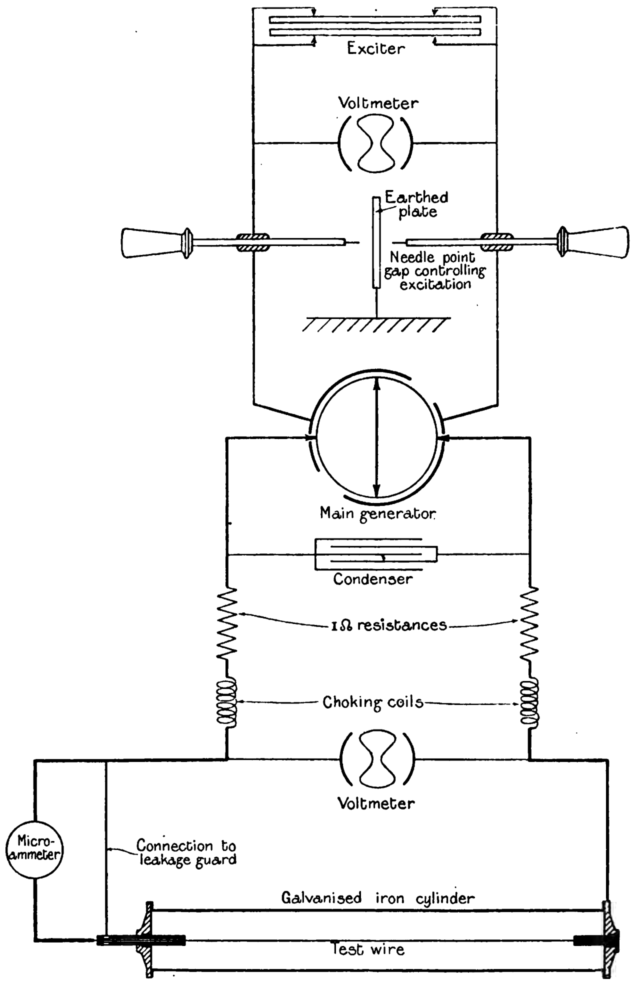

FIG. 3.—Diagram of Connections.

Generally, however, when the current density was sufficient there developed on the wire a thin bluish purple film which appeared uinformly to envelope it. A slight hissing noise accompanied the discharge.

When the wire was negative the film was absent, and its place was

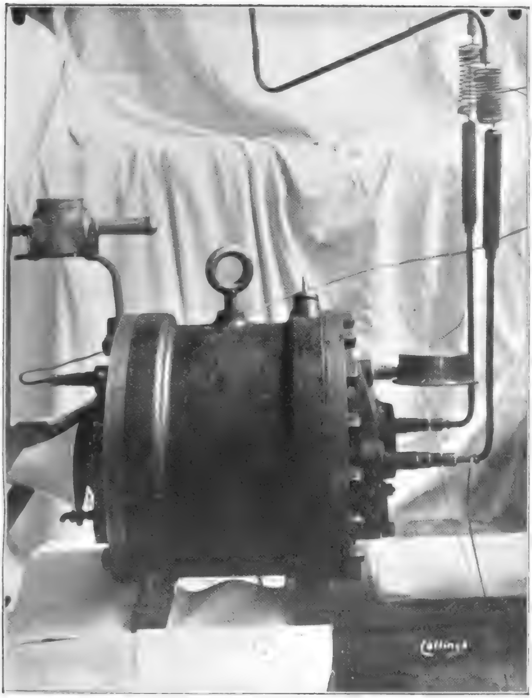

FIG. 4.—Influence Machine used in Tests.

FIG. 5.—Measuring Instruments used in Tests.

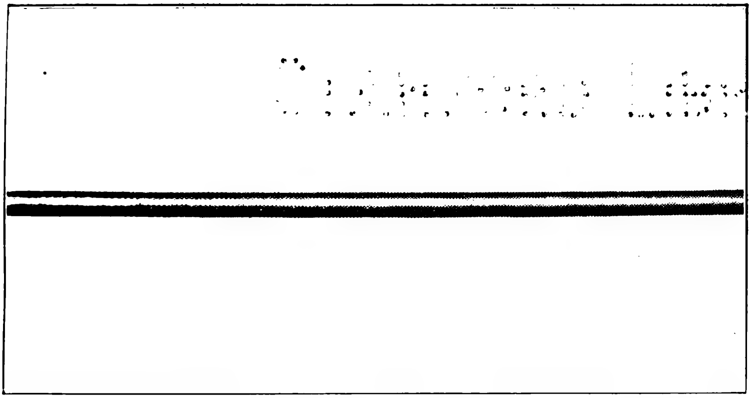

FIG. 6.—Wire "Dead."

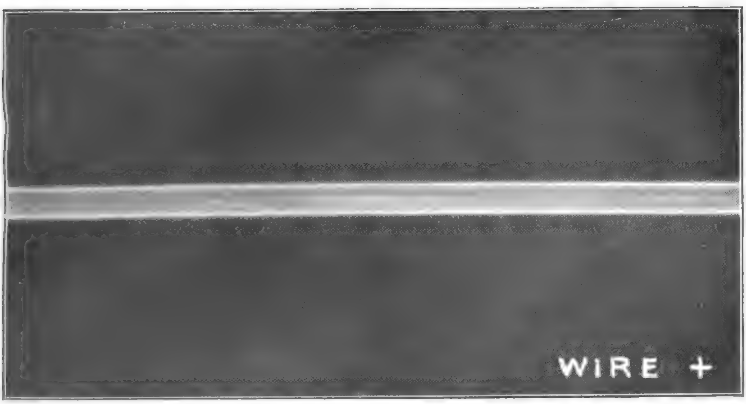

FIG. 7.

FIG. 8.

Showing Appearance of Wire when Surrounded by a Corona.

taken by a sort of halo of fine reddish-coloured discharges 3 to 5 mm. long going out practically radially from the wire; these discharges were very nearly stationary and much brighter than the corresponding positive ones, and were accompanied by a loud hissing noise which could be heard quite distinctly above the hum of the machinery in the room.

The positive corona seemed very little affected whether the wire were dirty or clean, but the negative one was very sensitive to the state of the surface. With the wire negative any small particles of dirt seemed to cause the discharge to concentrate itself upon it, each particle of

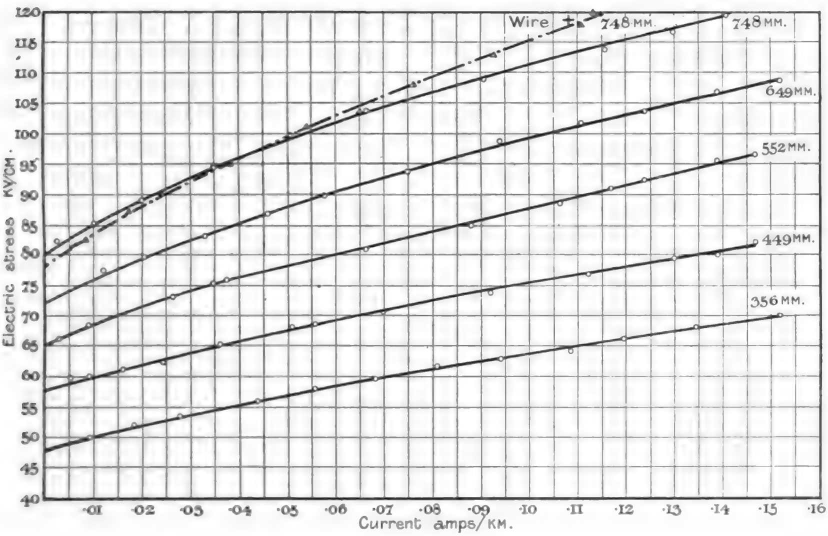

FIG. 9.—Relation of Current lost to Electric Stress.

Wire, 0·70 mm. diameter.

The figures on the curves give the air pressure in millimetres of mercury.

dirt giving rise to a tuft of bright reddish light about 5 mm. long, which gave a strong wind; the discharge, moreover, was much less noisy, and if the wire were dirty enough very nearly silent.

Figs. 6, 7, and 8 illustrate this effect. Fig. 6 shows the wire "dead" in order to compare its size with the coronas shown in Figs. 7 and 8, which are taken from the same point as Fig. 6.

The bright spot seen in the middle of Fig. 8 is due to one of the tufts of light just mentioned. When the wire was quite clean both positive and negative coronæ required very nearly the same voltage to start them. If anything, the negative one required slightly the higher, but the difference was not more than 3 per cent. at the very outside.

There was, however, a difference once the corona was started in

regard to the slope of the curve connecting voltage and current loss, the value of $\frac{dI}{dV}$ being greater when the wire was negative than when it was positive. This will be seen from Fig. 9, where the chain-dotted curve is for a positive corona, while the full-line one is for a negative. When, however, the wire was dirty, there was a great difference between the positive and negative conditions. With the wire positive the critical voltage was not much affected by the presence of dirt, but when it was negative discharge occurred at a much lower voltage; moreover, there was a great

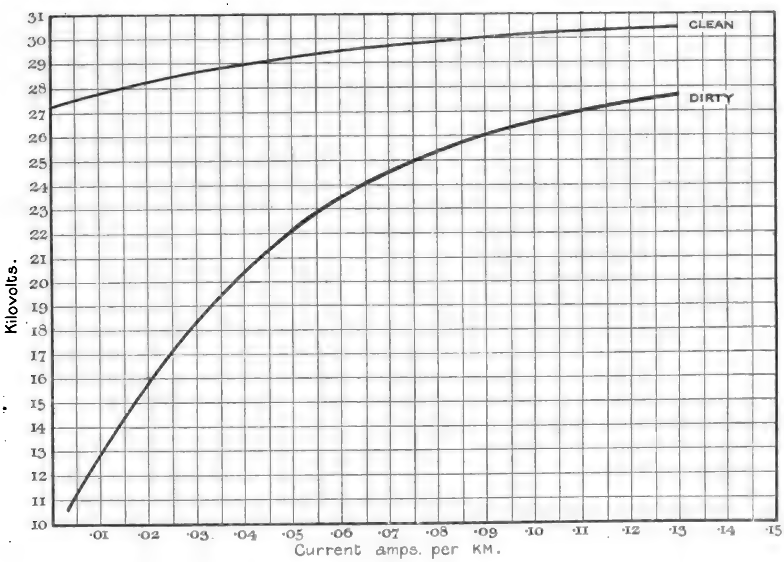

FIG. 10.—Comparison of Clean and Dirty Wires.

difference in the shape of the curve connecting current loss and voltage. The loss, instead of beginning sharply at some definite voltage, commenced slowly, and the curve gradually turned round so as to approach that for a perfectly clean wire. This is shown in Fig. 10, which gives the curves obtained with a wire 1·85 mm. diameter both when clean and dirty. The similarity of the curve for the dirty wire to that of Mershon's Niagara tests shown in Fig. 2 will be apparent.

Figs. 9 and 11–18 give some of the results obtained with wires of gradually increasing diameter from 0·70 to 12·76 mm. They also show the effect of variations in the atmospheric pressure upon the loss and critical point.

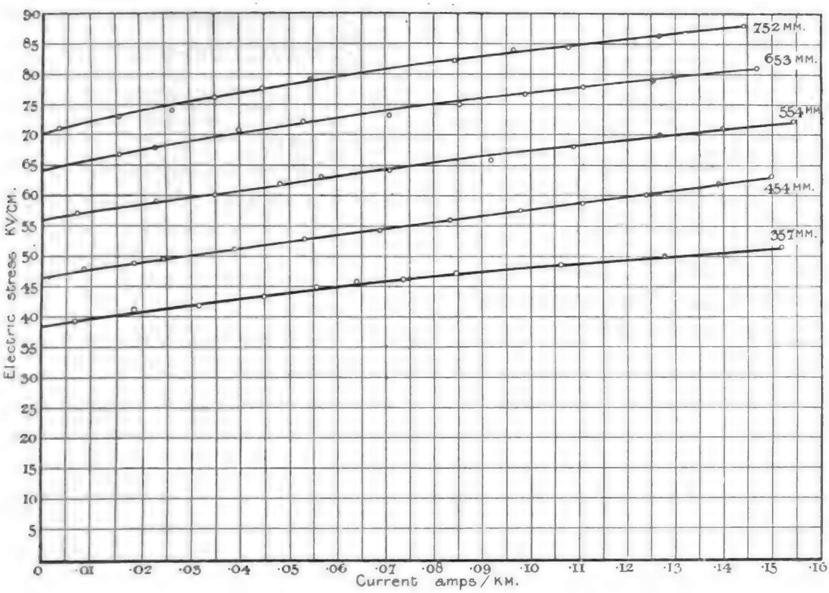

FIG. 11.—Relation of Current lost to Electric Stress.

Wire, 1·195 mm. diameter.

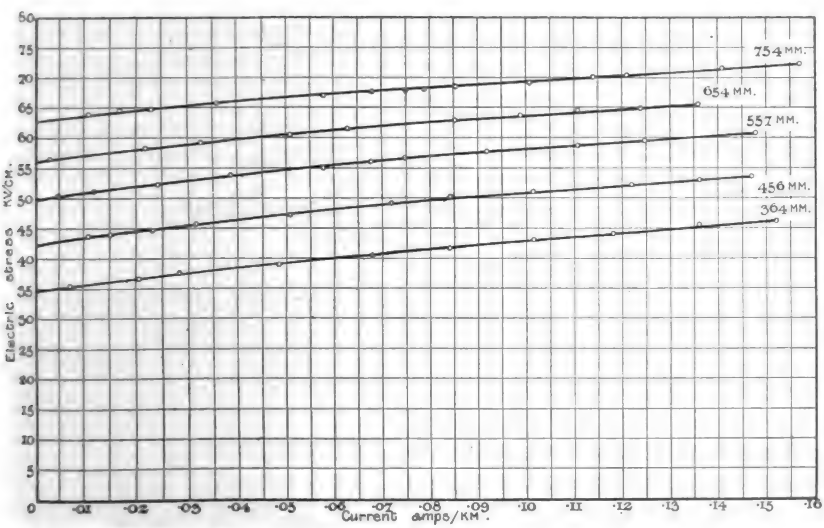

FIG. 12.—Relation of Current lost to Electric Stress.

Wire, 1·85 mm. diameter.

Two things will be noticed from a general inspection of these curves: Firstly, the increasing value of $\frac{dI}{dV}$ with the size of the wire; and secondly, the decreasing value of the critical electric stress.

The first of these is, of course, only natural owing to the increasing surface presented by the wire, but the second might, perhaps, hardly be expected. It does not, of course, mean that the actual voltage required to start a corona decreased as the wire diameter increased. That was not the case, but the value of the electric stress, as found from the expression on page 3, showed a steady downward tendency falling from 81·4 for the 0·70 mm. wire to 40·2 for the 9·53 mm. one.

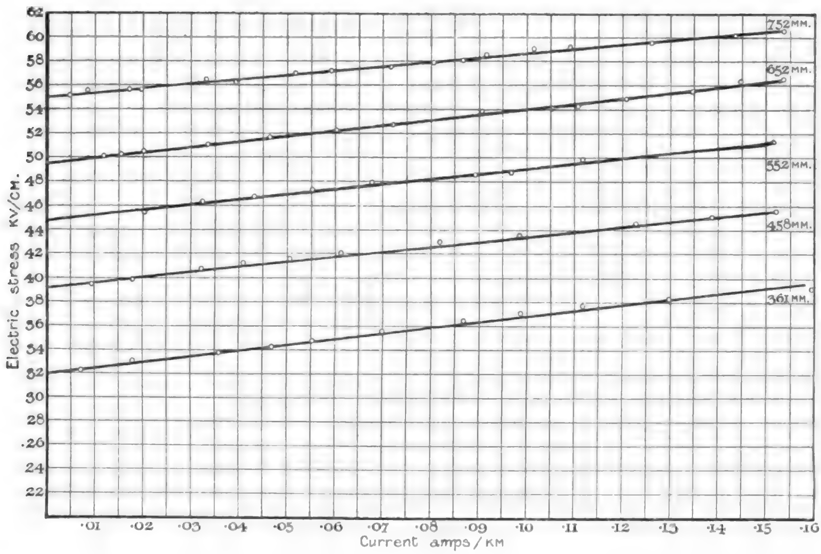

FIG. 13.—Relation of Current lost to Electric Stress.

Wire, 2·64 mm. diameter.

It is stated by some authorities that the explanation of this apparent decrease of electric strength is to be found in the assumption of a constant potential drop occurring at the boundary of the wire, this being the same for all sizes, so that we may write—

$$\frac{V - E}{a \log \frac{b}{a}} = \text{constant} = R_o,$$

where E is the constant voltage drop in question. This gives—

$$V = R_o a \log \frac{b}{a} + E.$$

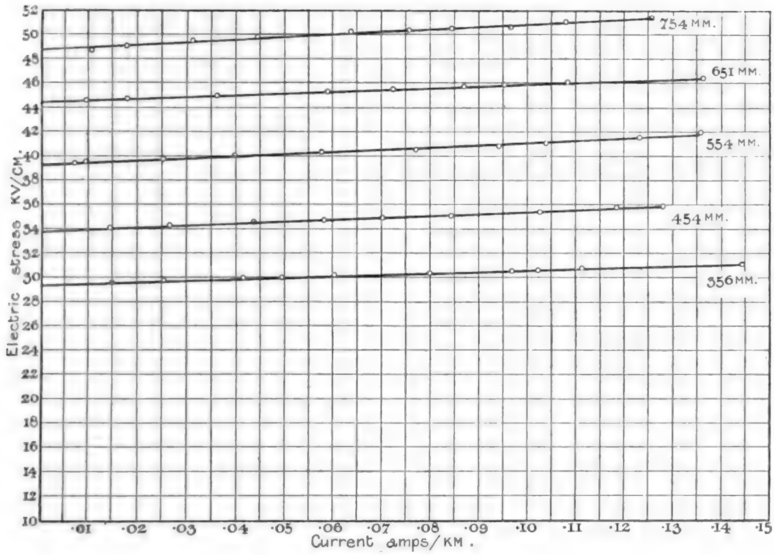

FIG. 14.—Relation of Current lost to Electric Stress.
Wire, 4·1 mm. diameter.

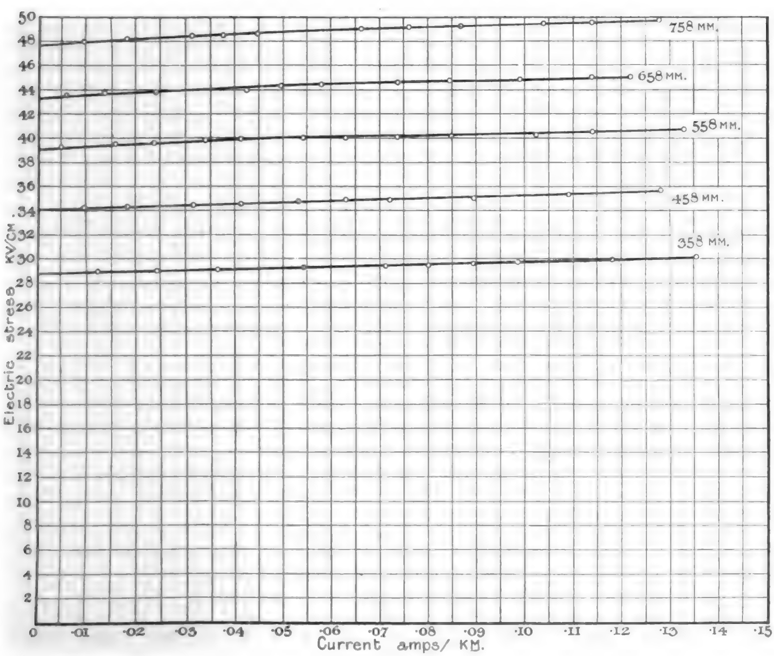

FIG. 15—Relation of Current lost to Electric Stress.
Wire, 4·76 mm. diameter.

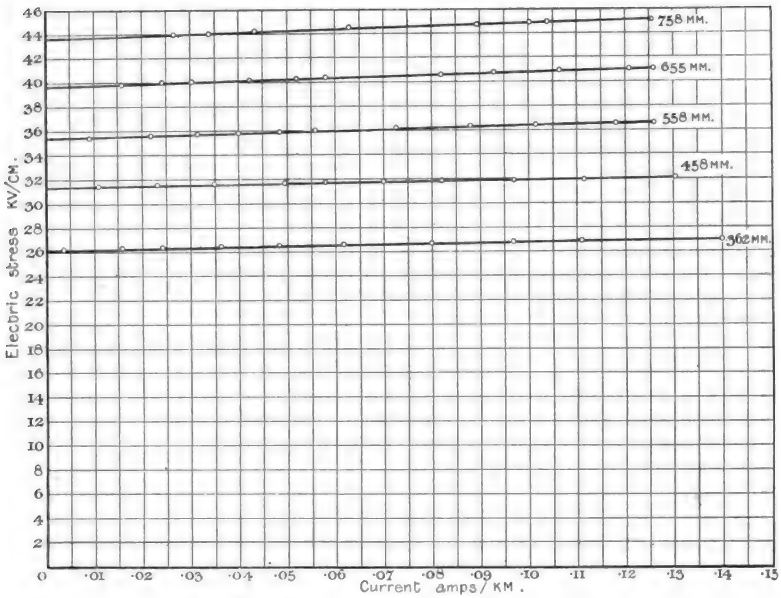

FIG. 16.—Relation of Current lost to Electric Stress.

Wire, 6·35 mm. diameter.

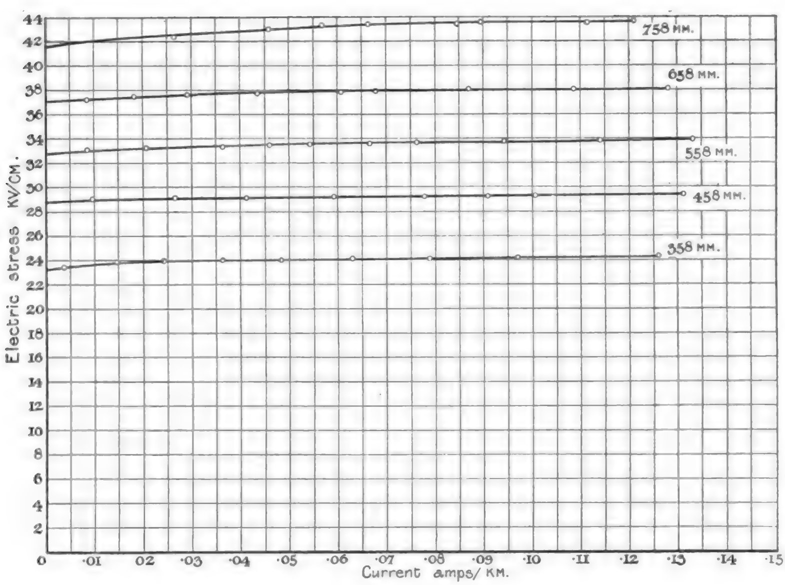

FIG. 17.—Relation of Current lost to Electric Stress.

Wire, 8·07 mm. diameter.

If this holds we should on plotting V against $a \log \frac{b}{a}$ obtain a straight line passing through the point

$$a \log \frac{b}{a} = 0, \qquad V = E,$$

and thus obtain the value of E and R_0.

If this be done for the points in question, the points obtained will be found to lie not on a straight line but upon a curve concave to the axis of $a \log \frac{b}{a}$. Moreover, if a straight line be drawn tangential to the curve for points between $a \log \frac{b}{a} = 0{\cdot}6$ and $1{\cdot}2$ it will be found to give values of E ranging between 10 and 20 kilovolts—*i.e.*, in the latter case actually more than the observed critical voltage for the smaller wire.

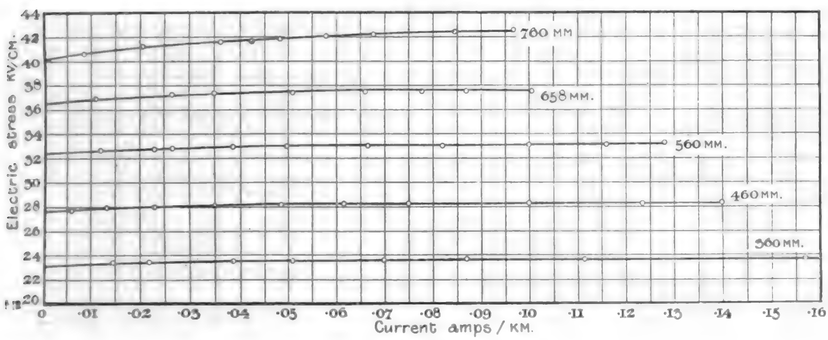

FIG. 18.—Relation of Current lost to Electric Stress.

Wire, 9·53 mm. diameter.

It does not therefore appear as if this explanation is a satisfactory one, and, to the author's mind, a far more reasonable one lies in the assumption that the layers of air near the wire or, in fact, near any conducting surface, have an electric strength greater than that of the main body. This is an old idea and has been suggested by Steinmetz, Ryan, and others. It will readily explain the high values of electric strength obtained with the small wires as the thickness of the layer of electrically strong air is greater in proportion to a small wire than a large one. It is supported by the fact that the thin films formed in certain electrolytes such as are used in electrolytic rectifiers and lightning arresters are known to possess an abnormally high electric strength. It is also supported by the following fact observed in connection with the above tests :—

When the wire was positive to the tube it was found that for wires more than 6 mm. diameter a disruptive discharge occurred instead

of a corona. Now it can be easily shown that if the electric strength of air were constant this could not occur unless the diameter of the wire was more than $\frac{1}{2 \cdot 718}$ of the diameter of the cylinder. The wire was actually much less than this, and we can only conclude that the electric strength was not constant but decreased the further one went from the wire, so that once the discharge started actual disruption occurred.

If we accept this hypothesis we can find the relation between distance from surface of conductor and electric strength by the construction shown in Fig. 20. In this has been plotted against distance

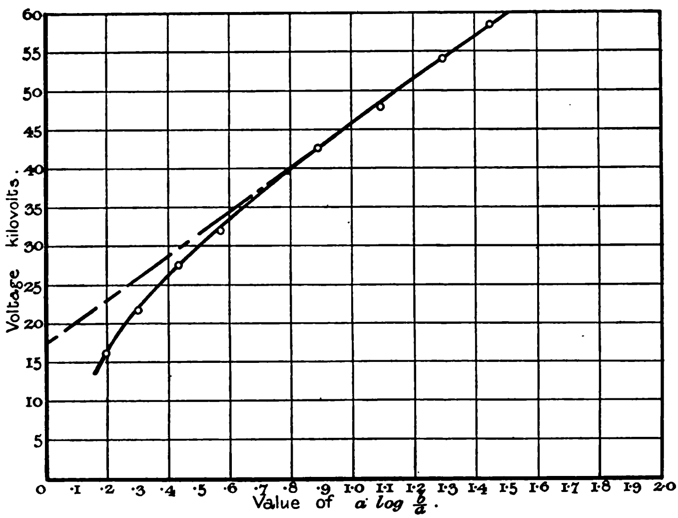

FIG. 19.

from conductor surface the value of the electric stress at that distance due to the charge on the wire. This is equal to—

$$R_a \times \frac{a}{r}$$

where—

R_a = stress at surface of wire.
r = distance of point considered from centre of wire.
a = radius of wire.

At some point this curve must touch the curve expressing the electric strength of the air—it cannot cut it. Hence, if a number of such curves are drawn for different wire diameters their envelope will give the relation between electric strength and distance from conductor surface which is desired.

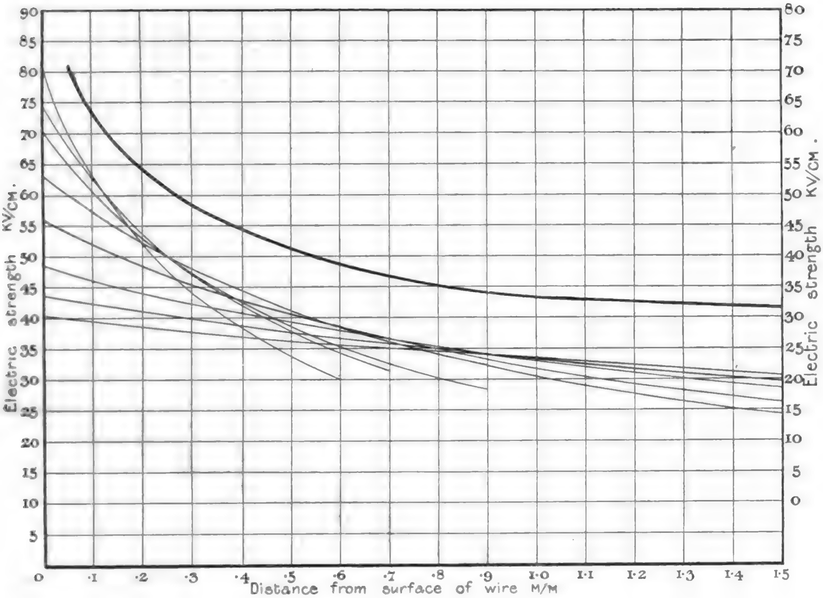

FIG. 20.—Method of Deducing the Electric Strength of Air.

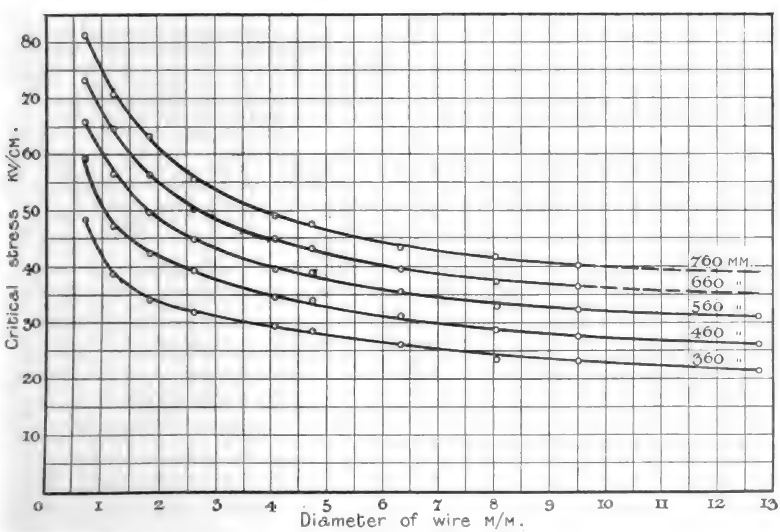

FIG. 21.—Variation of Apparent Electric Strength with Diameter of Wire.

This curve is shown in Fig. 20; it has for convenience, and to avoid confusing the figure, been moved bodily upwards and must be used with the right-hand scale of ordinates.

Comparison of above Results with Other Experimenters.

In Fig. 21 are plotted the values of the electric strength of air deduced from these experiments against the diameter of the conductor employed. If these are compared with the values of electric strength given in Fig. 1 they will be seen to agree very well indeed with the upper batch of figures given there—*i.e.*, with Ryan's and the Telluride

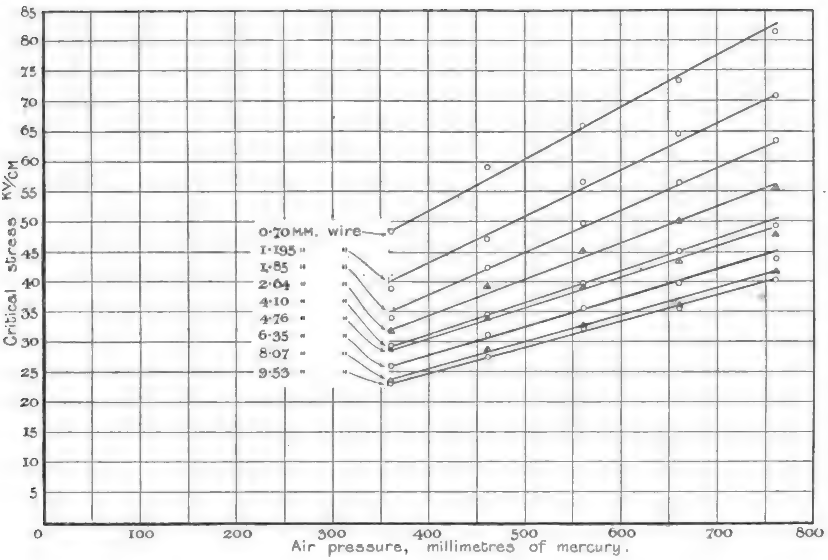

FIG. 22.—Variation of Electric Strength with Air Pressure.

measurements—but are considerably higher than given by Mershon's tests. The conditions, however, more resembled those of the former than the latter experiments, so that such an agreement is really highly satisfactory. It seems to show that the critical voltage is the same both for alternating- and direct-current pressures, provided that in every case the maximum value of the impressed voltage is taken as the determining factor. It would therefore appear that the frequency of supply in an alternating-current system will make no difference to the critical voltage, although it will, of course, considerably affect the losses after the critical voltage has been passed.

The second conclusion to be drawn from the curves is the effect of atmospheric pressure upon the critical stress.

This is shown in Fig. 22. As far as can be told from the readings taken, this is represented by a straight line which does not, however, pass through the origin, giving if produced back a residual electric strength for zero air pressure. Of course this is not actually the case, and the curve bends down somewhere, but between $\frac{1}{3}$ atmosphere and 1 atmosphere it seems to be practically straight.

An equation which appears to fit the lines for all the wires very fairly well is—

$$R = R_0 \left(0{\cdot}2 + 0{\cdot}8 \frac{P}{760}\right),$$

where—

R_0 is the electric strength at 760 mm.
P is the barometric pressure considered.
R is the electric strength at that pressure.

(It should be stated that the temperature during the experiments was 17° C.)

This result is rather higher than that obtained on a wire 0·125 in. diameter by Professor Ryan, who obtains a straight line having the equation—

$$R = R_0 \left(0{\cdot}115 + 0{\cdot}885 \frac{p}{760}\right).$$

This wire is, however, smaller than most of those used in the foregoing experiments.

An attempt was made to determine whether the presence of water vapour had any effect upon the critical stress, the cylinder being filled with dry air, which was then drawn out by the pump, moist air being allowed to take its place. No noticeable effect should, however, be observed, both the starting-point of the corona and the loss remaining unaffected.

If these figures are to be applied to the case of an alternating-current line it must be remembered that the voltages given are the maximum values and must for that case be divided by the amplitude factor.

It now remains to consider the tests which were made upon the two parallel wires hung out of doors. It can hardly be claimed that these tests are anything like as complete or conclusive as those which were carried out on the wire and cylinder, as they were very much limited by the apparatus which was available, chiefly by the generator.

This, as has been mentioned, could only work up to 70,000 volts, whereas to obtain results with wires of the sizes normally employed in transmission work would have required voltages of 200,000 to 300,000. As mentioned earlier, an arrangement was made for connecting another machine in series with the main one, but the current given by this one was so small that no definite corona or critical point could be observed. As a consequence of this tests could only be

made on small-sized wires (diameters of 0·70 mm., 1·195 mm., and 1·65 mm. being employed), and one had to be content with attempting to predict from these what would be the behaviour of larger ones were it possible to employ them.

It would doubtless have been highly desirable to carry the measurements up to more practical dimensions, but this was not possible. The influence machine employed had to be specially made for the purpose in order to get sufficient output, and no other was available to put in series with it. It is hoped that when another influence machine of sufficient output has been built, it will be possible to obtain some tests at higher voltages.

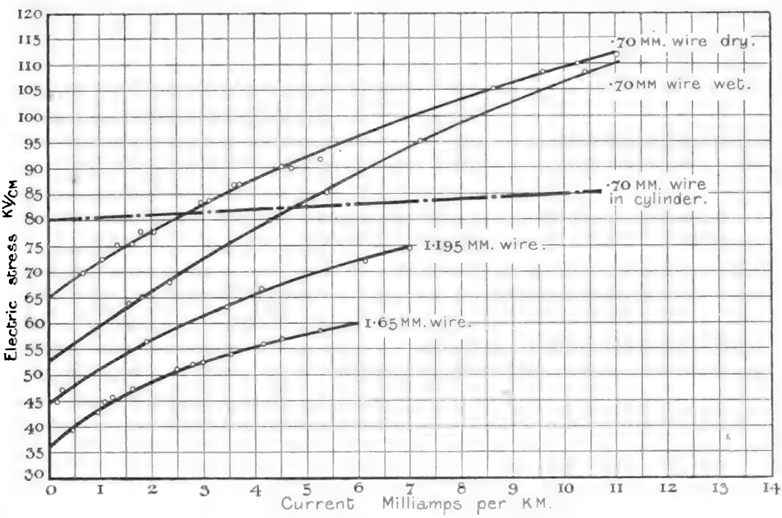

FIG. 23.—Results of Tests on Wires hung Out-of-doors.

Of the tests which were carried out special attention should be paid to the one on the 0·70 mm. wire, as this is the most complete and affords the best basis for comparison with the wire, in cylinder tests.

It will be seen in Fig. 23 that two curves are given for the wire, one for it when dry and another when wet. The first was taken on a dry summer day with very little water vapour present, the second on a day when a strong wind and driving rain were blowing in from the sea.

It is probable that these two curves represent the extremes between which the losses lie for all ordinary country anywhere in the neighbourhood of towns or industrial centres. The curve for the wet wire probably represents the very worst that would occur in this country, as the weather conditions were very unfavourable and the atmosphere not altogether free from smoke and fumes of various sorts.

The second thing to be noted is that the values of the critical stress given by the curves are considerably lower than those obtained from the tests of the wire in the cylinder, being for the dry wire only 65 instead of 81·4 k.v./cms.

It will be observed also that the two curves for the wet and dry wires, although starting at considerably different values, gradually approach one another and show a tendency to run together.

The explanation of these effects is believed to lie in the fact that the wire being dirty was not behaving in quite the same way as when tested in the cylinder. A large loss would probably occur before the wire was uniformly surrounded by a true corona, and it is conceivable that upon a loss occurring in this manner the presence of moisture might produce some effect which would not occur for a perfectly clean wire.

The tendency of the two curves for the wet and dry state of the wire to run together is explainable on this assumption as the loss prior to the formation of the true corona, which alone is affected by the presence of water vapour, would become relatively of less importance after the corona had formed and as the loss was increased.

Another peculiarity of these results is that the value of $\frac{dI}{dV}$ is much less than it was for the case of the wire in the cylinder—*i.e.*, a given increase of voltage above the critical one produced a much smaller increase in the value of the current lost per kilometre of line. This was not expected, as it was thought that the rate at which the ions would leave the surface of wire would depend simply upon the potential gradient in its neighbourhood which was urging them forward, and would be uninfluenced by the manner in which the gradient was produced, whether by placing the wire in a concentric cylinder or parallel to another wire. This should certainly be the case were the potential gradient near the wire settled only by the ordinary electrostatic laws, but it seems probable that once a discharge has commenced this will not be the case, as the distribution of electric stress will be affected by the presence of the charge carrying ions which permeate the surrounding space. It seems, indeed, very probable that the electric stresses shown on the curves as existing at the wire after the corona has formed are only apparent and do not really exist.

It was hoped when the experiments on the parallel wires were started that it would be possible to obtain some factor by which to multiply the values of electric stress obtained from the tests on the wire in the cylinder in order to obtain values which could be used if designing an actual line. It can hardly be claimed that the tests given enable one to do this with certainty without allowing a considerable margin. Judging from the tests given, a factor of safety of 2 would cover all ordinary cases and one of still less, say 1·7 to 1·8, would probably be sufficient. It is true that the larger wires appear from Fig. 23 to require a bigger factor of safety than the one of 0·70 mm.,

but it was not possible to carry the voltage high enough to obtain a definite corona with these sizes, and the distribution of loss may not have been uniform, being possibly greater at the ends (which were near to buildings) than in the middle. It is worthy of note that the ratios by which Ryan's tests on the wire in the cylinder exceed Mershon's Niagara experiments vary from 1·73 for a wire 2·5 mm. diameter to 1·59 for one of 10 mm.

General Summary.

1. That there is a definite critical stress for which loss occurs from a direct-current line just as for an alternating-current one.

2. That the direct-current stress required to produce this loss is the same as the maximum alternating-current one.

3. That this stress is substantially the same whether the wire is positive or negative provided that it is clean.

4. That for dirty wires the electric stress is lowered much more for negative than for positive charges.

5. That the critical stress is greater the smaller the wire diameter.

6. That the critical stress is reduced by reduction of the air pressure but not proportionately.

7. That the presence of water vapour in the air does not affect the loss or critical stress for a clean wire.

8. That an actual transmission line does not behave exactly like a perfectly clean wire, but that a factor of safety varying from 1·5 to 2 should be allowed. This factor probably depends somewhat on the conditions of the district in which the wire is situated and is probably less for a line in a clean mountainous region than for one in an industrial district. The loss is also affected by the presence of water vapour in the atmosphere especially for low values of the electric stress, and a considerable loss takes place before the wire is uniformly enveloped in a corona or becomes noticeably luminous.

9. That the loss which occurs with direct current when the critical stress is exceeded is due to the production of gaseous ions at the surface of the wire.

10. That the actual current lost depends partly upon the amount by which the stress at the wire exceeds the critical value and partly upon the disposition of the wires.

11. That with alternating-current lines part of the loss may be due to the energy stored in the layers of air surrounding the wire and which upon breakdown becomes converted into heat, but that this is insufficient to account for the whole loss which is observed and that part of the loss is probably due to the same cause as that for direct currents.

In conclusion, the writer would express his thanks to the University of Liverpool for facilities for carrying out the work, and to Professor E. W. Marchant for much advice and assistance during its progress.

References.

C. F. Scott. "High Voltage Power Transmission," *Transactions of the American Institute of Electrical Engineers*, vol. 15, p. 531, 1908.

H. J. Ryan. "The Conductivity of the Atmosphere at High Voltages," *Transactions of the American Institute of Electrical Engineers*, vol. 23, p. 101, 1904.

R. D. Mershon. "High Voltage Measurements at Niagara," *Proceedings of the American Institute of Electrical Engineers*, vol. 27, p. 1027, 1908.

Jona. "Report of High Tension Power Transmission," Committee of the American Institute of Electrical Engineers.

J. Stark. "Die Elektrizität in Gasen," Winkelmann's *Handbuch der Physik*, 2nd ed., vol. 4, pp. 454–654. Leipzig, 1905.

A. Righi. "Il Moto dei Ioni nella Scariche Elettriche." 2nd. ed. Bologna, 1905.

J. J. Thomson. "Conduction of Electricity through Gases." 2nd ed. Cambridge, 1906.

L. Lyndon. "The Corona Effect and its Influence on the Design of High Tension Transmission Lines." *American Institute of Electrical Engineers*. Philadelphia Section, November 9, 1909.

Discussion.

Mr. J. S. Highfield: I think the results the author has obtained may have considerable practical value, but the researches need to be carried further. In making tests with direct current on the leakage due to air discharge, leakage over insulators, and the like, one of the greatest difficulties is to obtain a sufficiently high direct-current pressure with any amperes behind the volts; and with the ordinary influence machine it is impossible to get anything like sufficient watts to conduct such experiments. Mr. Watson appears to have devised or used a machine which gives results very much superior to anything I have heard of before, and I hope he will give us a description of his apparatus. As regards the method of conducting the direct-current experiments, he carries the wire into its supporting tube through a pierced insulator, and then lands the other end of the wire on to a fixed insulator. I know that he takes precautions to determine the amount of leakage on the ingoing side, but I have not quite followed how he measures the leakage over the insulators inside the tube. I asked M. Thury, who has done so much work with high-pressure direct currents, for some figures as to the actual losses over long transmission lines, and he tells me there is one direct-current transmission line having a total length of 180 km., 360 km. of wire of 9 mm. diameter, working at a pressure of from 50,000 to 60,000 volts. The current is constant at 75 amperes. [The President: Is that to earth or wire to wire?] Wire to wire. There are very good ammeters fixed at the power station at one end and at the receiving station at the other, and the Mr. Highfield.

Mr. Highfield.

loss off that line with its thousands of insulators is negligible. On the Lausanne line there are 3,000 insulators and about 72 km. of wire, and the line can be charged up to its full pressure of 23,000 volts direct current by means of an exceedingly small machine giving about $\frac{1}{10}$ ampere all told. Perhaps I have not followed the figures in the paper exactly, but the losses ascertained in the paper do not quite agree with the actual losses over these long lines in practice. Possibly the difference is due to the different conditions between the overhead line and Mr. Watson's test tube. It is interesting to note that the critical pressure from Mr. Watson's tests for the maximum point of an alternating-current pressure is the same as for a direct-current pressure, so that with a sine wave it would follow that the stresses on the insulators at 140,000 volts direct current would be the same as at 100,000 volts alternating current. In practice, however, the breaking-down stress for direct current is not one-half that of alternating current. The curves in Fig. 23 show two sets of tests, one from tests made on the wire in the tube, and one from the two wires supported parallel. I am not quite sure that Mr. Watson is satisfied that he has found the true factor to connect the results of these tests. From the shapes of the curves I should gather it was difficult to get an exact factor. I think further tests on the parallel wires would be extremely valuable, especially if made under actual conditions of practice, and I have no doubt that with further improvement of the influence machine such tests will be made.

Dr. Russell.

Dr. A. RUSSELL : The brush discharge from the line only limits the permissible voltage when bare wires are used. The radiation of electricity from high-tension overhead wires can be prevented by wrapping an insulating material of great electric strength round them, the procedure being analogous to that of putting a suitable packing round steam pipes to prevent heat radiation. In my opinion the corona with alternating pressure is in phase with the pressure. This can easily be tested by a stroboscopic monocular, in the same way as the light coming from an alternating arc is tested. If the frequency of the current be low enough, the coronæ should appear to be rotating round the three wires, like the light from the three lamps in the Siemens synchronising device, when the 3-phase machines are not in step with one another. In connection with the Telluride tests, the author states that they were made at a great altitude in the mountains. The barometer reading would therefore be low, and consequently the electric strength of the air ought to have come out appreciably less than in the other tests. Mr. Watson's calculations as to the expenditure of energy due to the corona eating up the Faraday tubes are interesting but not convincing. They assume that the corona is a conductor, the effective size of the conductors being thus increased. Their capacity would therefore be increased and their self-inductance diminished, both of which effects increase the charging current, and therefore the losses. Further electrical calculations in this connection, although interesting, are not of immediate practical value, as the bulk of the losses are pro-

Dr. Russell.

bably due to mechanical and chemical actions. The hypothesis that every conductor has a layer of air round it which is electrically stronger than ordinary air is crude and unnecessary. Near the critical pressure the ionisation round the conductors begins, and so the electric stress on the air close to the conductor is relieved. Hence it is not the fact of this air having greater electric strength that prevents the disruptive discharge from occurring, but merely the fact that it is subjected to a less electric stress than we are led to expect from calculations founded on the assumption that there is no electric charge in the air round the conductor. I am strongly of opinion that the electric strength of air in a given physical condition is a real physical constant, and I have never seen any experimental results which could not be explained on this assumption. The conclusion that the author deduces from his experiment with a wire inside a cylinder is not the only possible one. Another and more probable conclusion is that the mathematical equations do not apply owing to the ionisation of the air round the inner conductor. It is interesting to remember that as far back as 1866 Gaugain proved roughly that when the ratio of the diameter of the inner conductor to that of the outer was a large fraction, the disruptive discharge seemed to be governed by the maximum value of the electric stress. The experimental results given in Fig. 21 should prove very useful. Steinmetz's experimental results* show that the apparent electric strength of air with 8 mm. wires is 40·7 kilovolts per centimetre, and with 28 mm. wires that it is 36·2 kilovolts per centimetre. These results agree excellently with Mr. Watson's, considering the great differences in the methods of experimenting. The speaker has recently carried out experiments with direct pressures on sparking voltages in air between spherical electrodes of very unequal sizes. The results seem to show that the apparent electric strength of air is 3 or 4 per cent. higher when the small electrode is negative than when it is positive, which is probably due to the greater ionisation round the negative conductor. A reference to the photographs shown in Figs. 6 and 8 supports this view. I agree in general with Mr. Watson's conclusions, interpreting "substantially the same" in No. 3 as meaning "within 3 or 4 per cent."

Mr. Rayner

Mr. E. H. Rayner: Mr. Watson has a cylinder with insulators passing through the metal ends; connected between the generator and central wire there is the ammeter and guard-tube arrangement. I have found in high-voltage work that it is useful to invert the arrangement. The potential stress on the wire is greatest at the ends of the tube, and leakage takes place around the wire where the lines of stress are concentrated before it takes place nearer the centre of the wire where the lines are radial. The leakage at the ends may be omitted from the current measured by the ammeter by connecting the latter to the centre of the tube, which is divided into three parts, the two end parts being lightly insulated from the centre part and connected to the

* *Transactions of the American Institute of Electrical Engineers*, vol. 15, p. 281, 1898.

Mr. Rayner.

circuit, as shown in Fig. A. I have used this method, which is practically a copy of Kelvin's "guard ring," for wattmeter measurements of insulating materials. It is possible to avoid all the trouble of brush discharge from the edges of the electrode by using a method of this kind, and measuring the energy lost in the material alone. A few weeks ago I was working on the same lines as Mr. Watson, but in quite a different manner, and I do not know whether to be more surprised or pleased at the concordance between us. On page 15 Mr. Watson gives us, as Mr. Highfield has remarked, a picture of the influence machine, but only as taken from the outside. I venture to say that a picture of the inside would also be extremely useful. Those of us who have to deal with high voltage can manage the alternating current pretty well, if we have a reasonable amount of money, but the high-voltage continuous current is rather a hard nut to crack. I should be

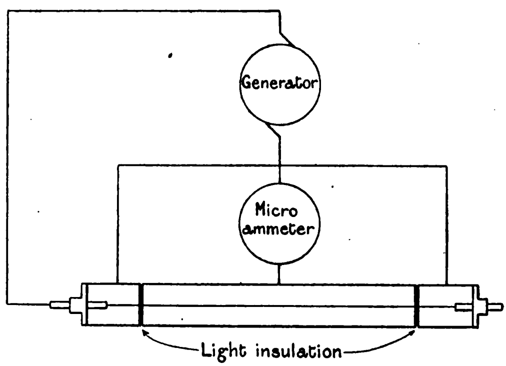

FIG. A.

greatly obliged if the author will give us some details as to the output of this machine at various voltages—say 20,000, 30,000, 40,000, and 50,000 volts. If any but a very small current be taken out, down go the volts, and that limits the output. To those who have to consider the question of apparatus, some little information as to the output of a high-voltage, continuous-current machine is always very useful.

As to the matter of dirty wires, I have not noticed any trouble, but it seems that in using a very thin wire the dirt would act so as virtually to increase the diameter of the wire and reduce the stress, while naturally a spot of dirt on a larger wire would increase the local stress in the air. I have been using smaller wires than Mr. Watson has for certain reasons, and the matter is of some little interest. My own experiments have been founded on work for the Engineering Standards Committee on insulating materials. In the research which is now going on at the National Physical Laboratory, I was not satisfied with an ordinary voltmeter and breaking down the insulation piece after piece. With the

help of the literature on the subject I constructed a wattmeter to measure the actual watt losses in insulation much in the same way that Mr. Addenbrooke has done. A wattmeter is an extremely simple thing to make, and it works well. By working it with the needle at half the supply voltage (in itself a great advantage) all corrections for the current resistance can be avoided. I designed the wattmeter to be used at 10,000 volts, and it works satisfactorily up to about 15,000. In experimenting on insulating materials, chiefly varnished cloth, I came to the conclusion that it was extremely important to take account of the air between the layers; that the dielectric loss in the air was sufficiently great to heat up the material and ruin it. This was one of the reasons why I went into the question of air losses; and also because I

Mr. Rayner.

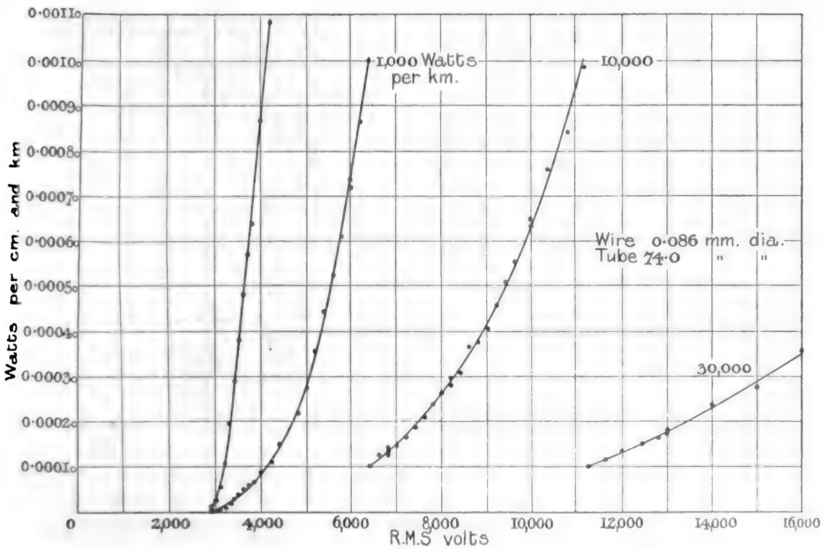

FIG. B.

wanted to get at some of these physical constant factors, and in particular to obtain some measurement of the dielectric strength of air, and to find the point at which watt losses begin, and this wattmeter gave me the means of doing it. I first tried a concentric tube and wire, as Mr. Watson has done. The tube was quite small, about 8 in. long and $\frac{9}{16}$ in. diameter. The results were so promising that I considered a larger tube would be preferable, and used one 3 ft. long and 3 in. diameter. I hung down the centre of the tube, which was open at both ends, wires of various sizes which extended beyond the tube at both ends. I used thin wires partly because the wattmeter voltage was limited, and partly because I thought that with very small diameters some interesting results might be expected. The thinnest wire was

Mr. Rayner.

less than $\frac{1}{10}$ mm. in diameter. The results are shown in Fig. B. The scale of ordinates is the watts lost round the wire per centimetre of length (or, by multiplying by 100,000 per kilometre of length). It will be seen that the first measurement was made at 2,900 volts, and the energy lost was about one hundred thousandth of a watt per centimetre length of wire. As the wire was about 1 m. long, the wattmeter measured about one thousandth of a watt. At 3,000 volts this corresponds to about the three millionth part of an ampere. Even if this were not completely drowned in the capacity current it would hardly be practicable to measure it, so that a wattmeter becomes a necessity

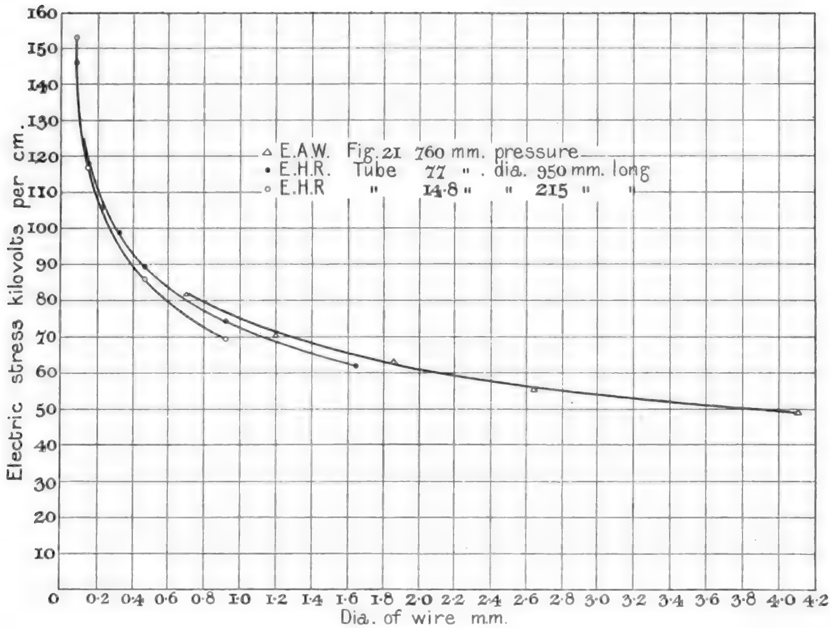

FIG. C

for work of this kind with alternating current, and luckily it can be made much more sensitive than any practicable alternating-current ammeter.

The rapid rise in the watts to 4,200 volts shows that the loss increases rapidly with the voltage. At this point the scale of ordinates has been multiplied by 10 and the curve redrawn. The scale has been further multiplied by 10 and yet again, showing a loss of some 36,000 watts per km. at 16,000 volts. The actual watt loss round the wire in this case was about 34, and this appreciably heated the air in the tube and also the tube itself. Under these conditions the watt loss increased with time of application of the voltage as the air warmed up, even at

Mr. Rayner.

voltages considerably below the highest employed. I now come to the point where my results may be compared with Mr. Watson's. It will be understood that the wattmeter affords a very delicate instrument, not only for measuring power but for detecting when loss in the air round the wire commences. By using wires of various diameters and observing the voltages at which loss commences, a curve can be drawn connecting the electric stress in the air at the surface of the wire and

EXPERIMENTS ON ELECTRIC STRENGTH OF AIR BETWEEN WIRE OF RADIUS (a) CM. AND CONCENTRIC TUBE OF RADIUS ($b = 3{\cdot}7$ cm.). FREQUENCY ABOUT 50.

a.	b/a.	$a \log b/a$.	V R.M.S.	R R.M.S.	1·41 R.
0·0043	860·0	0·0290	3,000	103,500	146,000
0·0072	515·0	0·0450	3,800	84,500	119,000
0·0115	322·0	0·0664	5,000	75,400	106,000
0·0160	231·0	0·0870	6,100	70,200	99,000
0·0230	161·0	0·1168	7,400	63,400	89,400
0·0460	80·5	0·2015	10,600	52,600	74,200
0·0820	45·0	0·3130	13,800	44,000	62,000

[*Note.*—In the first line I have put 3,000 as the voltage at which watt-measurements with the thinnest wire are detectable. In compiling the table I chose a higher value when there was any doubt. On plotting the curve, Fig. A, the value 2,900 as mentioned in the discussion would probably be justified.]

the diameter of the wire as Mr. Watson has done (Fig. 21). In the case of alternating current it is usually recognised that the peak of the E.M.F.-wave is the voltage to be considered, and as my voltage curve is very nearly sinusoidal, I have assumed a factor of 1·41 to represent the ratio of the maximum value of the voltage to the R.M.S. values as measured by the voltmeter. On the diagram (Fig. C) I have reproduced the results of Mr. Watson as plotted in the upper curve (Fig. 21) at 760 mm. pressure as nearly as I could, and the one a little below it gives the results obtained from the larger tube and seven different sizes of wire. The lowest curve on the left shows the preliminary results obtained with the smaller tube. The lower values obtained might possibly be due to the increased error in centering wire and tube, which was simply done by inspection. Below are the figures relating to the

Mr. Rayner.

experiments. The agreement between the two upper curves cannot but be considered remarkable having regard to the different methods by which the results have been obtained. Assuming the factor 1·41 to be correct, the two curves show, with more accurate experimental data than have probably yet been obtained, the truth of the statement usually made that the maximum value of the E.M.F. curve is equivalent to the corresponding continuous voltage.

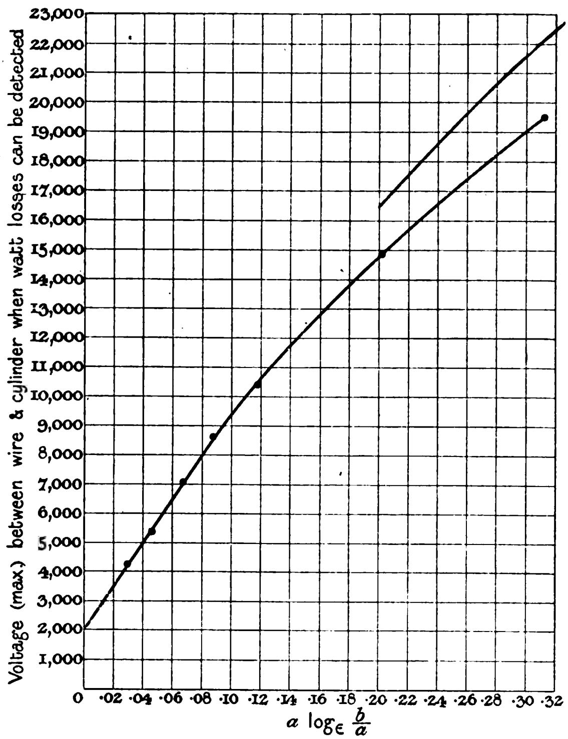

Fig. D.

The third diagram which I have to show, Fig. D, is one corresponding to Fig. 19. I have redrawn the bottom left portion of this on a much enlarged scale and put in the lower portion of Mr. Watson's curve as accurately as I could. It will be noted that my thinnest wire takes the value of $a \log \frac{b}{a}$ down to about 0·03, corresponding to about $\frac{1}{20}$ in. on Mr. Watson's diagram, and that the continuation of the curve to the axis cuts the latter at about 2,000. The physical meaning of this, or whether still finer wires would show different results, I am not prepared to discuss. Finally, I would add that I have so far regarded my ex-

periments as little more than preliminary, and had no intention of publishing them at present, but Mr. Watson's experiments have entirely modified that attitude. Mr. Rayner.

Mr. J. S. S. COOPER: In the first four words of his paper the author sets aside all commercial considerations. Yet, as a limiting factor in the transmission of power, the corona presents a commercial rather than a technical difficulty. So far as is known, it can be avoided for any voltage by sufficiently increasing the outside diameter of the conductor. If it proved worth while, copper tubing could be substituted for a solid copper conductor. Mr. Russell has pointed out that an insulating covering could be employed. This again is a purely commercial question. The necessary and sufficient condition for justifying any such expedient is that the saving effected by increased efficiency due to the high voltage shall pay interest and depreciation on the extra outlay. It is possible that the limits imposed by the corona may prove a considerable factor in the choice between copper and aluminium transmission lines. For a given resistance per mile the aluminium conductor has a diameter about 30 per cent. larger than the copper, and, roughly, half the weight. Apart from the question of first cost, aluminium has a number of points of inferiority in comparison with copper, one of which is its relatively low scrap value. But the advantage of the increased diameter is, at limiting voltages, another weight thrown in the opposite scale, and may then be the means of turning the balance. The author does not anywhere state the material of his wires. This, of course, amounts to a tacit assumption that the corona effect is purely physical. In the tests made by Mershon at Niagara the loss was found to be greater for an aluminium wire than for a copper wire of the same diameter. This does not necessarily prove that the effect has a chemical factor, for it may be due to the difference in texture of the surfaces of these two metals. It is well known that some metals, including zinc, are capable of producing ionisation under the action of daylight, and this suggests another possible explanation. It would be important to decide by conclusive tests whether there was any practical difference between common metals as regards critical voltage and brush-discharge losses. The construction of Fig. 20 is both ingenious and suggestive. Mr. Russell has remarked that it rests on certain assumptions which may not be applicable to the case considered. But if, for the moment, the principle of this construction is admitted and is pushed to its logical conclusion, some curious ideas may be deduced. Imagine the thick curve in this figure to be already drawn, and that below it is drawn the curve of electric stress in the neighbourhood of a certain wire at a voltage well below the critical. If the voltage on the wire is now raised, and the curve keeps pace with the change, the curve will move up the paper, retaining its general shape unchanged. At the moment when the critical voltage for this particular diameter of wire is reached this curve will coincide with one of the thin curves shown in Fig. 20, and will touch the envelope curve. At this same moment breakdown will begin at a distance from the Mr. Cooper.

Mr. Cooper.

wire represented by the abscissa of the point of (geometrical) contact. The breakdown of this cylindrical layer of air will increase the stress on the neighbouring layers, and the breakdown or corona will spread inwards to the surface of the conductor and outward until equilibrium is established. The assumption of the truth of the hypotheses on which the figure is based thus leads to the conclusion that breakdown never begins from the surface of a wire unless its diameter is infinitely small. This result is rather at variance with accepted notions, and renders it probable that the hypotheses on which it rests are inapplicable to the conditions of the tests.

Mr. Hobart.

Mr. H. M. HOBART: As regards its immediate practical bearings, the most important point that I have noted which has been dealt with in the discussion is the confirmation of Mr. Watson's third conclusion by Mr. Rayner and also (within 4 or 5 per cent.) by Dr. Russell. This conclusion is that the handicap of transmission of alternating current, as compared with transmission of continuous current, is, so far as concerns the working pressure, of the order of 40 per cent., *i.e.*, the continuous system is on the same basis as the alternating system when the pressure is 140,000 volts continuous as against 100,000 volts alternating, instead of, as claimed by the advocates of the Thury system, that an alternating pressure of 70,000 volts is equivalent, as regards the insulation of the system, to a continuous pressure of 140,000 volts if the alternating pressure has a sine wave-form. Mr. J. S. Highfield,* in an interesting paper describing the Thury system, gave us to understand that the ratio of advantage of the continuous system was of the order of 2 to 1, and that conclusion was accepted by a good many who took part in the discussion. Lord Kelvin, who presided on that occasion, concurred in that view, only reserving an expression of considerable surprise that it was the case. All the other speakers whom I remember, except myself, fell in with the view, but I ventured at that time to point out that the tests were exceedingly crude and were far from sufficiently conclusive. I analysed some of the tests which were included in Mr. Highfield's paper, and I found that in many cases the ratio was 41 per cent., and in fact the very tests on which Mr. Highfield based the 2 : 1 ratio, when carefully examined, were equally indicative of a 1·41 : 1·00 ratio. I consider this a matter of very great interest, because the question of how to transmit electricity to a distance to the greatest advantage is one of very great importance. While I hold that the alternating system is beyond all comparison the best, not only from the standpoint of engineering soundness, but also, and chiefly, with respect to commercial economy; nevertheless, some attractive features are inherent in the continuous system, and since it is the task of engineers to arrive as nearly as possible to an agreement as to the best system, it is as well to subject all claims to thorough investigation, and here we have three authorities—Mr. Watson, Mr. Rayner, and Dr. Russell—all agreeing as to the correctness of the $\sqrt{2}$: 1 ratio as regards equivalent pressures.

* *Journal of the Institution of Electrical Engineers*, vol. 38, p. 471, 1907.

Mr. J. T. IRWIN: I wish to raise the question whether the voltage applied by the author is really a constant voltage. It was suggested to me by Professor Mather that the wave-form of an influence machine should be obtained. Fig. E shows the wave-form from a Wimshurst machine giving about 20,000 volts when it was supplying a leakage current of about 5 micro-amperes; the variation of voltage would become greater if a greater current were taken from the machine, unless the capacity of the condenser (which in the above case Mr. Irwin.

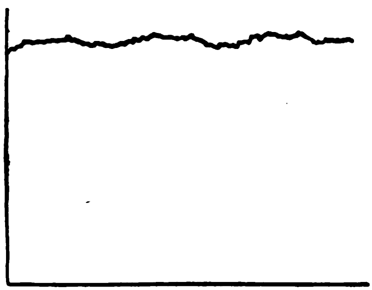

FIG. E.

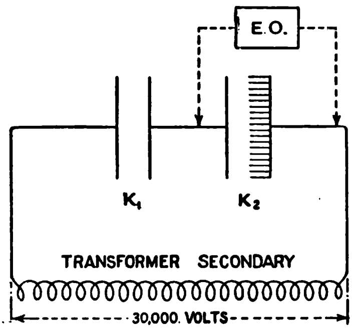

FIG. F.

was about 0·0001 of a microfarad) were increased. This and the following curves were taken on an electrostatic oscillograph. I also tried to reproduce at short notice a condition of affairs somewhat similar to those at the surface of a wire when the pressure is raised to a high value. Fig. F shows the arrangement where K_1 is a Leyden jar placed in series with an air condenser K_2. One of the plates in K_2 was plane, whilst the other had about 10,000 points projecting towards

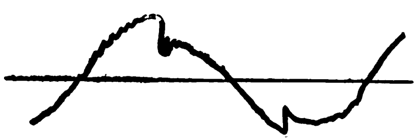

FIG G.

the plane plate; E. O. represents the electrostatic oscillograph which could be placed across K_1 or K_2. Pressures up to 30,000 (R.M.S.) volts could be put across the two condensers in series from the secondary of a transformer. The curve in Fig. G shows the pressure across the condenser K_2 when the voltage across the transformer was small; in this case it is seen that the voltage across the transformer only rose once during each half-period to a sufficiently high value to break down the air condenser. Fig. H shows the voltage curve across K_2 when the

Mr. Irwin. pressure across the transformer is high; in this case when the voltage breaks down the air condenser, the latter is recharged again to practically the same value, since the main voltage is still increasing; it then breaks down a second time, and is again recharged. The number of times it breaks down depends upon the charge that flows into the condenser K_1, and this obviously depends on the maximum

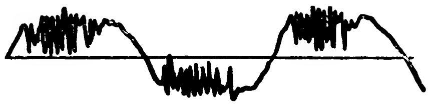

FIG. H.

voltage across the transformer. In considering the energy dissipated owing to the breakdown of the wire, Mr. Watson should therefore have considered the number of times per cycle the air broke down. Fig. I shows the voltage across the condenser K_1, when the voltage

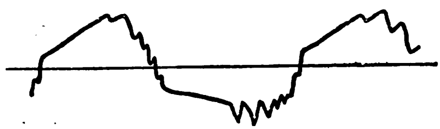

FIG. I.

across the transformer is intermediate between that for Figs. G and H. It shows that the voltages across the two condensers are not in phase, and gives the rise in voltage across the Leyden jar when the air condenser breaks down. These curves were complicated a little by the fact that a certain amount of rectification was taking place at the air condenser. The sensibility of the oscillograph had to be varied for the different voltages, so that the curves are not all to the same scale.

The President. The PRESIDENT: In calling upon the author to reply to the discussion, might I suggest to him to satisfy a desire which has been expressed by several of the members, namely, to add working drawings of the influence machine used. So many men are now working on this subject, that the addition of such drawings will be a great help to them. I understand that it was by working the machine in compressed air that he was able to get the high voltage required in his experiments, but apart from this general principle, there must be details of construction of which it would be useful to have a record in our Journal.

Mr. Watson. Mr. E. A. WATSON (*in reply*): Mr. Highfield raises the question of the supporting of the end of the wire in the tube and the possibility of any leakage over the support. The end of the wire was carried by a solid piece of ebonite rod about 9 in. long, the insulation resistance of which was infinite, as far as could be ascertained. There is con-

siderable difference between a solid insulator like this and one which has a wire passing through its centre, such as was used to bring the current into the apparatus. The presence of the central wire causes a very uneven distribution of electric stress on the outside of the insulator, which tends to cause leakage along its surface, in addition to which there is the danger of leakage through the material itself. A guard tube was therefore advisable in this case, whereas it was not required in the other. In order to ensure that the lines of force were not crowded and the stress concentrated at the ends of the wire, the ebonite of the terminals was thinned down at the end to a sharp edge. Observations of the wire in the dark showed that the brush discharge commenced simultaneously along the whole length of the wire and not at the ends first, proving that this device was effective. The losses obtained from the tests on the wire in the tube do not, as is stated in the paper, agree with those obtained from the parallel wires, the difference lying not so much in the voltage at which a loss begins as in the magnitude of the loss when the critical voltage is exceeded. This loss is always much greater for the tube tests than for the parallel wires, and the explanation, I believe, lies in the ease with which the ions produced by the discharge can, when the tube is used, get away and deliver up their charges. In the parallel wire case the distance they have to travel is much greater, and the average potential gradient driving them is much less. They therefore take longer on their journey, and the number of ions discharged in a given time is smaller, which means that the leakage off the line is less. During their journey to deliver up their charges it is only reasonable to suppose that the charge which they carry affects the value of the electric stress at the wire, tending to lower its value and prevent the production of fresh ions. The rate of discharge from the wire is thus automatically controlled and its magnitude will depend not only on the voltage applied and the apparent electric stress which it produces, but also on the arrangement of the wires in space. I am much interested in Dr. Russell's experiment showing the corona to be in phase with the voltage, and I agree with him in thinking that the greater part of the loss is due to mechanical and chemical effects. As regards the Telluride tests, allowance has been made for the altitude in working out the results. Since writing the paper I have seen an actual transmission line in Colorado working with a factor of safety of only about 1·25 in the higher parts of the line, which would certainly be impossible but for the cleanness of the air due to the great altitude. I am afraid that I still remain unconvinced by Dr. Russell's remarks as to ionisation around the wire being the cause of the higher apparent electric stress with small diameter. Once the discharge has commenced there is no doubt that ionisation would greatly modify the state of affairs, but the leakage off the wire begins so suddenly and definitely that I really cannot believe that there is any disturbing effect due to ionisation prior to the critical points. After all, we know that the molecular condition of a gas near to a solid surface is not quite the same as it is in the body of the gas itself, and I see

Mr. Watson.

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no obvious reason why the proximity of the solid should not affect the electric strength. Dr. Russell's result of an apparent electric strength 3 to 4 per cent. higher for negative than for positive charges agrees substantially with the curves shown in Fig. 9, where it is pointed out that when the wire was negative the critical stress was slightly the higher. I appreciate Mr. Rayner's suggested arrangement to obviate errors due to leakage at the ends. My reason for not employing it was the large size of the tube, and the difficulty of making sure that there was no leakage outwards off its surface. This could have been done by keeping it at about earth potential; but in order to the maximum voltage out of the influence machine it was necessary to have both poles alive, and there was a danger of losses taking place from small roughnesses and irregularities on the surface of the tube, or possibly due to slight ionisation of the air in the room. Mr. Rayner is quite correct about dirty wires. With small wires I experienced no trouble at all in getting consistent results, but with large ones it was very difficult indeed. Special cleaning arrangements were employed which could be operated from outside the tube after the wire was in place, and the inner surface of the tube was covered with sticky substances in order to collect and hold the dust. Even with these precautions, with a wire of 10 mm. and upwards in diameter, a great deal of care was necessary in order to get the required readings. I am very greatly interested in Mr. Rayner's electrostatic wattmeter, and must congratulate him on the results which he has obtained. I am pleased at their close agreement with my figures, and with the way in which they show the truth of the 1·41 ratio for alternating-current tests on a homogeneous medium such as air. I hope Mr. Rayner will be able to extend his tests to larger wires and also to carry out some experiments on parallel wires as well. Mr. Cooper points out quite rightly that the question of the corona is really a commercial difficulty. What I meant to imply was that at present in most cases the most economical voltage, having regard to cost of copper, insulators, apparatus, etc., is lower than that at which a corona would be formed, and it is only on the longest high-voltage systems that the question has so far become very important. The wires on which the tests were carried out were of hard-drawn brass, but the results appear to be independent of the material provided that the condition of the surface is the same. As aluminium has a tendency to weather to a rougher surface than copper, it is possible that it would give lower figures in practice. The curves in Fig. 20 certainly would seem to imply that the inner boundary of the corona is not the surface of the wire, and Ryan,* using alternating current, has actually observed a space between the two. It is true that the photographs do not show the existence of such a space, but with direct current once the discharge has started the conditions are somewhat different to those which obtain before the critical point is reached. Mr. Hobart raises the question of the 2 to 1 ratio for alternating and direct currents. While in a material like air the

* *Transactions of the American Institute of Electrical Engineers*, vol. 24, p. 101, 1904.

Mr. Watson.

advantage of direct to alternating current is only equal to $\sqrt{2}:1$, yet in a solid material which can become heated by an incipient discharge, and still more so in a composite dielectric, such, for instance, as is formed by air and an insulating solid, the advantage is much greater and can, I believe, quite easily attain the 2 to 1 value given by the advocates of the Thury system. I am very glad to see that Mr. Irwin's oscillograph is now completed and satisfactory; the curves which he has given are very interesting indeed. As to whether my influence machine was giving a steady voltage or not, the machine itself certainly gave a ripply current, but I believe that with the arrangement of condensers shown in Fig. 3 the voltage on the wire given by the machine was steady within less than 1 per cent.; the capacity of the condensers being increased until further addition made no difference to the values of the critical voltage read on the voltmeter. From Mr. Irwin's oscillograms it appears possible, however, that the actual discharge from the wire was intermittent in character, although the voltage impressed on it was steady. In fact, the hissing noise of the discharge would suggest this, and experiments on the question would be very useful. Several speakers have asked about the influence machine employed. I am afraid that I cannot give complete details as yet, as there are some points which I wish to protect. Briefly the machine is a multiplate machine running in compressed air. It has nine fixed plates 12½ in. and eight revolving plates 9 in. in diameter. The revolving plates are all carried on a common spindle and run in the same direction, the designed speed being 2,000 revs. per minute, although it was usually run about 1,200–1,400. Current is collected by means of small steel rollers running on the plates. The revolving plates are of ebonite with copper sectors buried in them, the stationary ones are plates only in name, for they consist of steel sectors about 14 B.W.G. riveted on to cross-pieces and carried off insulating supports. The insulation is therefore compressed air only, which at the pressures employed (150–200 lbs. per square inch) is equal to a solid dielectric and is not injured by any breakdown. For large currents the stationary sectors (12 in number) were grouped so as to give a multipolar arrangement, a revolving sector passing through six complete cycles during one revolution. For higher voltages and smaller currents they were grouped for a 2-pole arrangement as is customary in ordinary influence machines. The brushgear was arranged so that it could be rocked through a small angle in order to allow contact to be made with the sectors when at the same pressure as the collectors, thus securing sparkless collection. The machine was designed to give an output of 10 milliamperes at 100,000 volts when running at 2,000 revs. per minute. It has not yet given anything like this output owing to breakdown of the solid insulation of the revolving plates. Various substances have been tried, but it has not yet been possible to work the machine with a higher excitation pressure than about 40,000 volts without causing breakdown, the current breaking through the insulating material from the revolving sectors to the

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stationary ones. The compressed air insulation is designed to stand 200,000 volts excitation, and there is no doubt that were it possible to get the rest of the insulation to stand up to this figure the desired output would be more than obtained. Experiments are in progress to get over this difficulty and obtain a design which will not break down so easily, and it is hoped at some future date to be able to describe the machine more fully.

The President.

The PRESIDENT: Gentlemen, I now ask you to accord a hearty vote of thanks to Mr. Watson for his most interesting paper.

The resolution was carried with acclamation.

The meeting adjourned at 9.45 p.m.

Proceedings of the Five Hundred and Third Ordinary General Meeting of the Institution of Electrical Engineers, held in the Rooms of the Institution of Civil Engineers, Great George Street, Westminster, on Thursday evening, February 17, 1910 — Dr. GISBERT KAPP, President, in the chair.

The minutes of the Ordinary General Meeting held on February 10, 1910, were taken as read, and confirmed.

The list of candidates for election into the Institution was taken as read, and it was ordered that it should be suspended in the Library.

The following list of transfers was announced as having been approved by the Council :—

TRANSFERS.

From the class of Associate Members to that of Members :—

Alfred H. Burbidge.	Maurice Solomon.

From the class of Associates to that of Members :—

Arthur Frederick Guy.	Robert H. Houghton.

From the class of Associates to that of Associate Members :—

Benjamin Adair Malcolm Boyce.

From the class of Students to that of Associate Members :—

John J. Cardwell.	David S. Paxton.
Frederick Creedy.	Robert Rankin.
William P. Crooke.	H. R. Rivers-Moore.
Arthur Cunnington.	Charles E. Savage.
Arthur G. Gordon.	J. P. Stockbridge.
John F. Lochhead.	Harry Whitworth.

Messrs. A. Green and W. E. Butcher were appointed scrutineers of the ballot for the election of new members, and, at the end of the meeting, the following were declared to have been duly elected :—

ELECTIONS.

As Associate Members.

Arthur Stanley Angwin.
John Egerton Barnes.
Edward Barrs.
Harold George Brown.
James Brown.
Charles Crompton.
Richard Cunningham.
Percy Trevor Davies.
Robert Nicol Duncan.
Frederick Arthur Gaby.
William Leonard D. Gundry.
Edward Harlow.
Frederick William H. Hayes.
Francis Sydney G. Hinings.
Arthur Imbery.
William Ireland.
Edgar Joseph Ivison.
George Charles Jefferyes.
Francis Hugo Machugh.
Thomas Henry Matthewman.
Andrew James McDouall Murray.
James Hamilton Murray.
Frank Fitz Gerald O'Hagan.
John Patrick.
Faville Clement Poulton.
Thomas Edwin Scharffetter.
Edwin Slader.
Weldric Arthur Talbot.
Charles Edwin Tattersall.
John Waddell.
Roland Wheeler.

As Associate.

Lewis Hey Sharpe, B.Sc.

As Students.

Francis William D. Adcock.
James Allan.
Francis George Allen.
Aubrey Cyril Bowman.
Hugh Clark.
Raymond Henry Dryden.
Herman C. Hannam-Clark.
Charles Haydock Hill.
Kenneth Graeme Maxwell.
Robert Francis Niven.
Thomas Richard Parry.
Thomas David Todd.

The following paper (see page 49) was read and discussed: "Modern Electric Time Service," by Mr. F. Hope-Jones, Member.

MODERN ELECTRIC TIME SERVICE.

By F. HOPE-JONES, Member.

(*Paper received December* 2, 1909, *and read in London on February* 17, 1910.)

When I read a paper * before this Institution just ten years ago, electric clocks were at a very low ebb in this country. Towards the end of last century we had all been too busy with the more pressing problems of light and power to make any serious attempt to apply electricity to horology. The brief review then given showed that practically all the work of English inventors, including even that of Bain and Wheatstone, had been futile, the only survivals of the Victorian Era being the two forms of synchronisation, the Ritchie sympathetic pendulum, and the Lund minute hand clip, both of them necessarily very limited in their applications, while every attempt to introduce foreign systems had failed.

This was the position on the threshold of the present century when I introduced the "Synchronome" system to your notice. Some one had to prove that electric clocks, if constructed on sound principles, would work, and for five years it was left to me to do so. In that period three hundred or four hundred installations were erected, and these restored confidence and attracted others into the field. In 1905 no less than five systems sprang into active competition, and the business of electric time service which could hardly be established by one firm alone, however successful, was fairly launched as a branch of our profession.

The Council have consequently considered the subject worthy of an Institution evening, but I have now the rather more delicate task of describing the systems of others as well as the latest improvements in my own.

Representatives of these systems have, however, been invited here to-night, and I shall make my reading short so that they may make up in the discussion for any deficiency in my recital of their merits. It is practically impossible for me to do justice to other systems in a manner that would satisfy the inventors. In the first place, we have not time, and in the second, my sources of information are limited to what is published in their Patents and printed matter.

I must first remind you of the three classes into which the subject is divided :—

I. Self-wound clocks, independent of one another, which simply use electricity to provide their motive power.

* *Journal, Institution of Electrical Engineers,* vol. 29, p. 119, 1900.

II. Synchronising systems, in which a regulator or standard clock sends out electrical impulses to correct the hands of complete clocks having an independent life of their own.

III. Circuits of electrical impulse dials, in which a controller master clock, or transmitter, whether self-wound or key-wound, sends out electrical impulses at short intervals—*e.g.*, every half-minute or minute—to propel the hands of "receiver," "indicator," or "secondary" dials.

The first division does not come within the title of this paper, because it does nothing to strike at the root of the evil—the independence of clocks. It is true that a consulting electrical engineer only last year actually included in a county asylum specification thirty independent non-synchronised self-wound clocks, but we must pass him by for want of time to go over the old ground of collectivism *versus* individualism in clocks. That mistake is not likely to be made again. Yet there is such a subtle fascination about a self-wound clock that I have obtained specimens of nine of the best and set them going on the table. They are as follows: Hipp, Scott, Aron, Hoeft Müller, Synchronome, Reason, Eureka, Fery, and Self-Winding Clock Company, of Brooklyn, U.S.A. Automatic time switches for switching on and off electric light at pre-arranged times are usually isolated and cannot be grouped into time circuits. Their independence is therefore justified, and as accurate time-keeping is not necessary it is high time they were made self-winding by one of these methods, and that of the Reason Company was designed for the purpose. The Self-Winding Clock Company, of Brooklyn, U.S.A., comes within my classification because it is always fitted with a synchronising device, but I described that fully ten years ago, and nothing of importance in synchronisation has been achieved since then. I refrain from discussing applications of wireless telegraphy and pass on to—

Class III. Circuits of electrically-propelled dials.

The systems of electrical impulse dials which are of commercial importance to-day and which practically arrived in the year 1905 are those of Lowne, Aron, Perret, Magneta, and Gent. The systems of Campiche and Palmer (both of which arrived in that year also) are omitted because the amount of work yet done by them is hardly enough to justify their inclusion, but they should be mentioned because they were the first to give impulse to the pendulum in one substantial thrust every half-minute and to rotate a count wheel by the pendulum for that purpose, a method adopted by Lowne, "Synchronome," and Gent, and likely to be generally followed.

The time transmitter of Messrs. R. M. Lowne & Son, of Catford, is shown in Fig. 1. The pivoted crutch A (the pins at the bottom of which embrace the pendulum rod) has an extension at the top which carries the escapement rod B. The armature C is held up normally off the poles of the magnet by the flat steel spring E through the medium of the rod D. A pivoted catch lever is seen at F, and a gathering click

at G, which revolves wheel H once a minute, bringing one end of the lever J every half-minute into the position shown where it will form an obstruction in the path of the contact springs K mounted on the crutch A and swinging with the pendulum. The contact L being also normally closed, the magnet is energised on each fifteenth excursion to the left of the seconds pendulum, and power is restored in spring E.

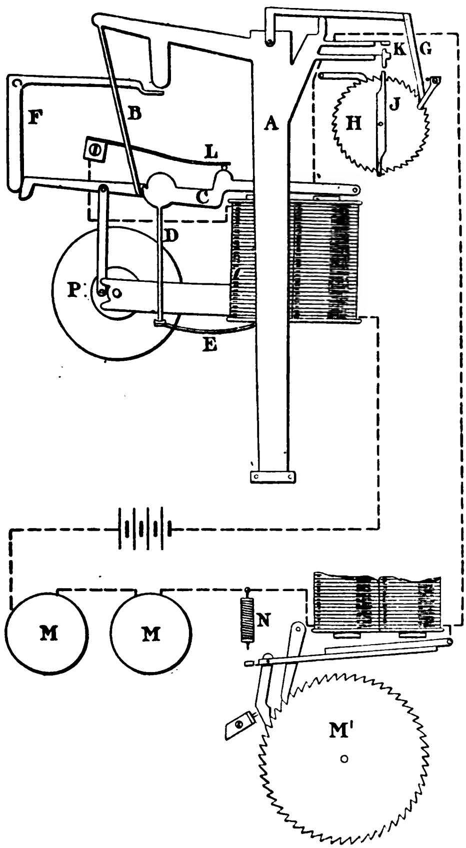


FIG. 1.

The series circuit includes the dials M, M, M', which are of the simple one-wheel step-by-step type similar to that described in my last paper, but provided with shunt coils N. The armature C, when it is thus pulled down, is caught by F, which holds it there until the pendulum on its next swing to the right releases it and allows the spring E to discharge itself into the pendulum through the medium of the escapement rod B.

A flywheel P is linked to the armature of the pendulum movement to slow its motion in order to make sure that contact L remains closed until the most sluggish dial has operated. The shunt coils N in the dials, by cutting out the resistance of each magnet as soon as it has operated, increase the current through those that require more, and thus it can be truly said that the current consumption is exactly that which the dials require. As an alternative to the inertia device P to prolong the duration of the contact L, two subsidiary transmitters may be used on the alternate circuit system where one makes and the other breaks. This is an elaboration of the electrical interlocking system described in my last paper, and it involves a device for halving the number of vibrations of the armature lever.

Though the propulsion of the pendulum might not satisfy the purists in that the pendulum is never absolutely free, that it does work at the end of its swing, and that all the energy for contact making is derived from it, it is nevertheless no surprise to me to hear of its excellent time-keeping performances as the details are of fine design and workmanship.

The Aron system is, of course, based upon Dr. Hermann Aron's self-winding action long successfully used in the meters of the Aron Electricity Meter Company, Ltd. It is illustrated in Fig. 2, in which the driving click A, mounted on the armature B, drives the main wheel of the clock by means of the spring C. The carrier D, with insulated blade E and contact blade F, is in a state of unstable equilibrium, and is adapted to be flung in one direction or another by the spring G when the contact pin H on the armature has moved it past the dead centre. It is used to self-wind what may be described as an ordinary striking clock in which the striking part has the sole duty of turning a commutator every minute, sending an impulse to the dials and reversing the polarity of the battery every time. In this respect they follow standard German practice which, in such systems as Grau-Wagner, of Wiesbaden, has entirely justified itself.

All attempts to produce systems with uni-directional impulses were abandoned on the Continent long ago, because they could not produce contacts perfectly clean and precise in make and break. Possibly they did not realise this as the real reason why their dials did not keep step, but they have been faithful to polarised dial movements for forty years in Germany for the sake of the security which they give. Every impulse might consist of a whole group of untidy splashes instead of a smooth-topped wave without a single polarised dial movement getting out of step. Consequently the oscillographs of impulses of uni-directional systems which we shall shortly be looking at will have no interest to those who have pinned their faith to the Continental method.

The self-winding action of Perret's system is shown in Fig. 3. Magnet A is placed vertically underneath armature H carried on lever C centred at B. The weight of this lever, plus spring R, is driving wheel F through the medium of click C_2. The wheel F is usually the

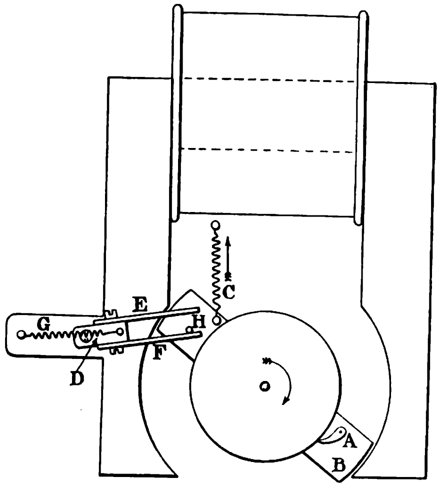


FIG. 2.

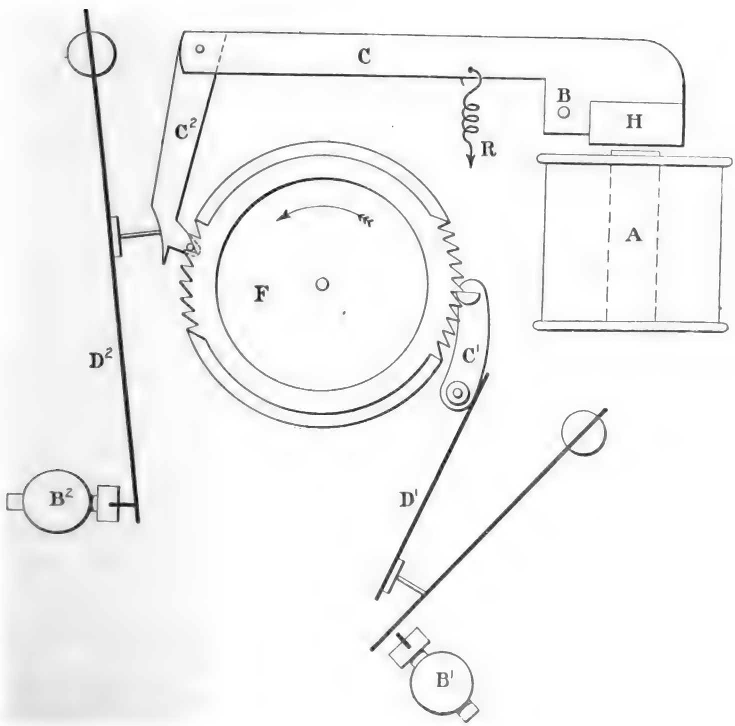


FIG. 3.

centre wheel of a watch escapement revolving once an hour and having 60 teeth. B_1 and B_2 are contact pillars and D_1 D_2 are spring contacts engaging with them and arranged to be opened and closed alternatively by the wheel through the medium of lever C_1 and driving click C_2. The contacts are in series, and as the driving lever C falls, D_2 B_2 is slowly made, D_1 B_1 being then open. C_1 now drops over the top of a tooth and D_1 B_1 is quickly closed, the magnet operated, and D_2 B_2 is quickly broken.

Though the contact is of the "touch-and-jump-away" sort, instead of "touch-and-follow-on," the functions are divided and the contact that jumps away is the one which was made substantially and at leisure when the circuit was open elsewhere. All the energy for contact purposes is derived from the wheel F or the armature which drives it, but little is required for a contact of this nature and fluctuations of driving force are small. It is limited to small currents and low voltage, relays being used for circuits of dials, which are of the simple one-wheel step-by-step type.

The watchmaker and jeweller in this country is still pushing electric clocks away from him with both hands. That has been the attitude of the trade from the beginning, and it is so still with a few notable exceptions. It is not unnatural that the man who wants clocks should go to the local clockmaker for them, even though he wants electric ones. But when he asks for them, he is solemnly warned off. Ultimately, the shopkeeper finds he has lost the order, perhaps for the time-keeping equipment of a large hospital or school, and that it has gone to the electrical profession. He is then bold enough to invest in a small trial installation, and this system appeals to him because of the inexpensive and portable form of the master clock. Colonel David Perret is an horological expert of great standing, with finely equipped factories at Neuchatel. He knows just how to make movements in the form suitable for the clockmaker to fit into any class of ornate case, and he permits them to be sold separately for that purpose, giving a substantial trade discount.

Not one clockmaker in a hundred in this country has the haziest notion of what an electrical clock is, whereas in Switzerland it has been an active part of their profession for a generation or two. Consequently I fear trouble with this system here through lack of expert handling which, good as the system is, I think it needs more than some of the systems to be mentioned later.

Ten years ago, when describing Wheatstone's induction system and the abortive attempts to use it in the Houses of Parliament and the Royal Institution of Great Britain in 1845, I little thought that his method was on the eve of a great revival, but at the very time I was recording the history of a failure, Herr Martin Fischer, of Zurich, was making history, and a success, by his applications of Wheatstone's principles which produced the "Magneta" system.

It will be recollected that Wheatstone generated alternate currents by means of the pendulum bob of his controlling clock, which was,

in fact, a magneto-electric machine driven by an enormously heavy weight wound by hand. The armatures in his dials revolved once for every complete vibration of the pendulum of the master clock, and were geared to the minute hand through a train of wheels. It is easy for us to see that his method could not hope to succeed in view of the flagrant violation of the rule, that the time-measuring function should never be combined with other duties. In Wheatstone's system the entire energy required to operate a circuit of propelled dials is derived from the one timing pendulum itself, an unwarrantable interference with the free action of gravity. And it is needless to say that the energy so obtained could never be sufficient to operate even a small group of dials with certainty.

Fischer made two radical improvements straight away; his magneto-electric generator was driven by a separate train of wheelwork, let off by the going train of a key-wound clock which was otherwise

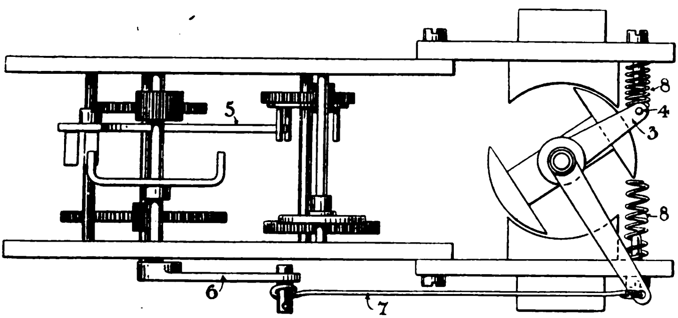


FIG. 4.

uninterfered with, and he generated his impulses once a minute instead of every second.

The arrangement is illustrated in Fig. 4, a horizontal section through the master clock. The releasing lever 5 forms the connection between the two trains of wheelwork, the power train on the left and the going train on the right. When the latter releases the lever at the end of a minute, the crank 6 is free to make one revolution, and by means of the connecting rod 7 it gives the armature a rapid to-and-fro vibration, banked by the springs 8, which not only reduce shock, but conserve some of the energy which would otherwise be lost in starting and stopping. The dial movements are, of course, of a polarised type, and are designed for quick action, leaving a spring to do the work of moving the hands.

In 1903 the Magneta Company were good enough to send me a report of a most exhaustive series of laboratory tests imitating extraneous induction interferences—a fine example of that German thoroughness which deserves to succeed—and I quote from a translation of it as follows: "As compared with Wheatstone's, the inductor possesses a

high degree of efficiency, the magnetic field being completely enclosed in iron. It works at a much higher speed, and a space available for the motion of the armature is unlimited. The duration of the impulses vary from 0·1 to 0·2 second, according to self-induction, etc."

When one has to take hold of small amounts of mechanical energy, isolated in point of time, and convert them into electrical energy, one is bound to lose most of it. Wheatstone dealt with a very small quantity every second, whereas Fischer deals with a much larger amount every minute, and consequently the loss is greatly reduced though still considerable. The limitations of such a system are obvious, and a master clock capable of operating a large circuit of small dials, or even a small circuit of large dials, must be both costly and cumbersome compared with one which has only to operate a switch. If a given dial requires 5 ft.-lbs. of energy per week to operate it, then (assuming an efficiency of 100 per cent.) 50 dials will require 250 ft.-lbs. to be stored in the master clock weekly, in addition to its own going power; but, as we have said, in the conversion of small mechanical energy into electricity and its reconversion into ft.-lbs. an efficiency of, say, 25 per cent. is the most we can hope to get, and consequently 1,000 ft.-lbs. will be required per week for 50 dials. In practice daily winding is usually resorted to, and though this reduces the necessary power storage to one-seventh, the size and cost of the master clock is still a difficulty in the case of large circuits, whilst the capacity of each master clock is limited, and if a time circuit requires to be extended it presumably would have to be changed.

The timekeeping of the Magneta master clock is well within its requirements because it is so constantly under the eye of the clock-winder. The accurate measurement of time for long periods by automatic means is a difficult yet alluring scientific problem with which they can have nothing to do unless and until they make their master clock self-winding. This has been suggested by means of a rotary motor in a method which will be described later on in connection with turret clocks; but can such a proposal be taken seriously? The motor would first convert current from the mains into foot-pounds in raising the weights of the master clock. In falling a little way every minute, the energy is reconverted into electricity for transmission to the dials, where it is once more converted into mechanical energy to move the hands. This roundabout method, with the heavy loss of efficiency involved in each stage of piecemeal conversion, would be necessary to enable the system to accomplish the same automatic result achieved by the modern battery system, which takes electrical energy from any convenient source, converting it into mechanical power in one simple operation wherever required. The justification claimed for the induction method is that the dials are in a permanently closed circuit, no contact being required to chop up an outside source of electricity into impulses. The inductor is operated by a train of wheelwork quite distinct from the going train which only has to release it, and consequently there is little, if any, interference with the time.

keeping properties of the high-class Graham dead-beat escapement used.

The motto, "No contact and no battery," inscribed upon the Magneta Company's banner, was most appropriate in every Continental country and in America, and secured for them an easy victory over the old-fashioned battery-driven systems, but I hope to demonstrate conclusively that both difficulties were overcome here years ago. It seems to me that the greatest virtue of the Magneta system is one which I have never heard them claim—the uniform wave-shape of their impulses—whilst its greatest drawbacks are the necessity of frequent winding, the loss in conversion and reconversion, and the consequent limitation of available power.

It was precisely from this point of view—faulty contacts and failing batteries—that the author of this paper approached the subject fifteen years ago, recognising it then as the main cause of the backward state of the science at that time compared with telegraphy, telephony, light, power, and other achievements of the nineteenth century.

The clockmaker who knew little of electricity put a pin on one of his gently moving wheels to engage a light spring, and made a poor contact, while the electrician, knowing little of horology, did the same with a stiffer spring, and stopped the clock or spoilt its timekeeping properties. That sort of thing had been going on for fifty years, and had ruined the reputation of electric clocks in this country, while abroad it drove Paris to a pneumatic system and produced complicated methods in Germany and Switzerland in which the current was reversed at each impulse.

Contacts operated mechanically by clockwork have the following vices :—

1. What small power is available for making them is robbed from the escapement.
2. They lack precision in the make and break.
3. Their duration is arbitrarily adjusted to their supposed requirements.
4. They pass what current is available regardless of its sufficiency or insufficiency.

In my Institution paper of ten years ago I described a simple mechanism called the "Synchronome" switch, which—

1. Had ample power, but took none of it from the pendulum or the escapement which drove it ;
2. Was perfectly clean and precise in the make and break ;
3. Gave impulses whose duration was largely dependent upon the self-induction of the electro-magnets they had to energise ;
4. Transmitted sufficient current to operate the dials, or else ceased work altogether.

The illustration from the *Journal* of that date is here reproduced as Fig. 5. The gravity lever C drives the wheel D, escapement B, and

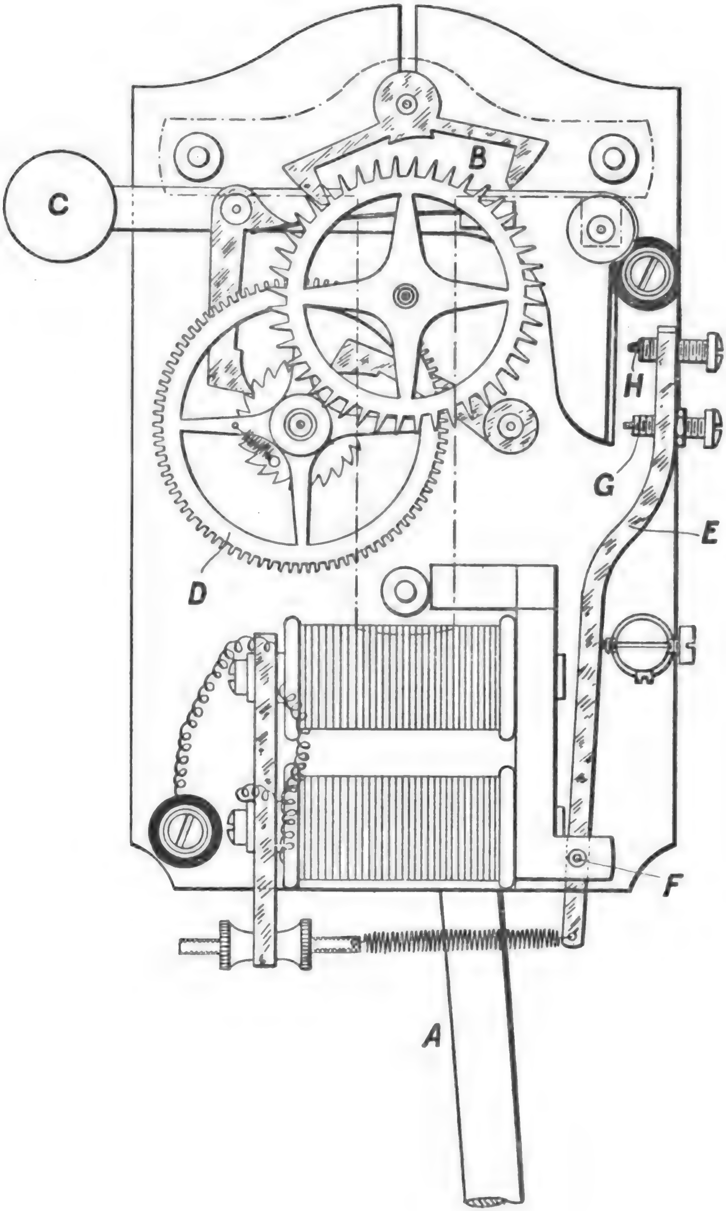


FIG. 5.

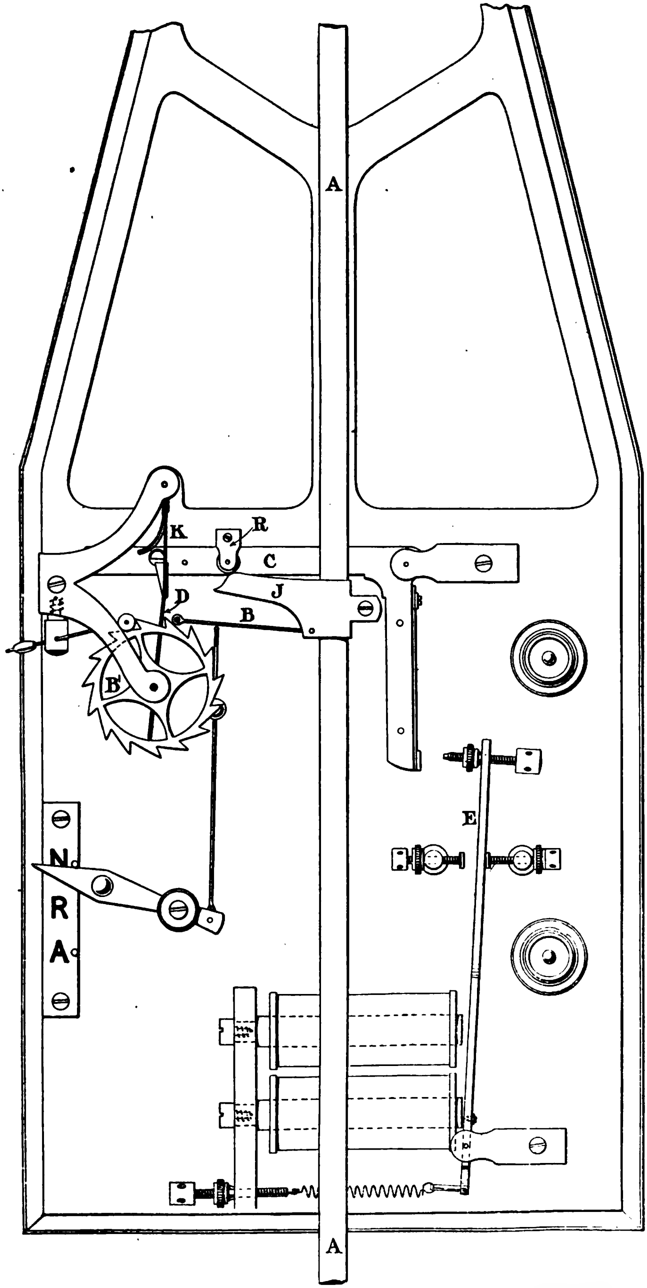


FIG. 6.

pendulum A in the usual way. When it reaches the contact screw G in the armature E the electro-magnet replaces the gravity lever on the next tooth of the ratchet.

In 1904, following Campiche, Palmer, and Lowne, the escapement was dispensed with and the gravity lever was left normally on a catch, withdrawn every half-minute by an otherwise idle count-wheel propelled by the pendulum. In its latest form it is illustrated in Fig. 6, in which the gravity lever C normally rests on catch K. Once every half-minute the lever C is let down (in the act of giving an impulse to the pendulum A) upon the contact screw in the armature E. Current from any available source then passes through the series circuit of dials and

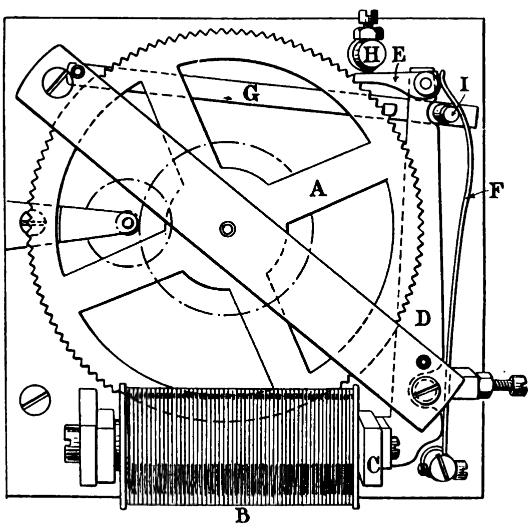


Fig. 7.

the magnet which attracts the armature E and throws the lever up on to its catch again.

The pendulum releases the switch by means of the 15-toothed wheel B^1, which carries a vane D engaging with the catch K at each revolution. The hook B pivoted upon the pendulum A turns this wheel once every 30 seconds. At the moment of its release the little roller R on the gravity arm C is just above the curved end of the pallet J, down which it runs, giving an impulse to the pendulum at the moment when it passes through its zero or central position. Thus the pendulum is free at all times except in the middle of its swing. The setting lever serves to stop the dials when moved from N (normal) to R (retard), or to accelerate them when moved to A. The method of impelling the pendulum as it passes through its zero position by the falling lever is well known in horology as the invention of Sir H. H. S.

Cunynghame, K.C.B., being an adaptation of his detached gravity escapement with free pendulum made as a mechanical clock in 1904.

In addition to the merits of the switch in its old form its two parts have a longer range of movement and sail into contact at the speed of the moving pendulum; when the current falls below a certain predetermined value the pendulum assists the magnet to replace the lever C, which action is a valuable indication of impending failure of battery, and if the pendulum stops it holds the switch open.

The dial movements illustrated in Fig. 7 are of the simple reciprocating armature type designed to deal with clock hands of considerable inertia and momentum, and made in five different sizes for clocks ranging from 3 in. to 10 ft. diameter. The wheel A has 120 rectangular teeth and carries the minute hand on its axle. The magnet B attracts the armature C mounted on lever D, by which means the click E picks up a tooth and the wheel is propelled by spring F. The backstop lever G and stops H and I are so arranged that the wheel is locked at every point in the cycle of operations, yet can be freed at once by raising the lever G.

The time transmitter of Messrs. Gent & Co., of Leicester, is very similar and is illustrated in Fig. 8. The gravity lever N is at the bottom with adjustable weight N_1 and the magnet above. The impulse surface R_1 is near the centre of the pendulum A, and the impulse roller P is seen just above it. The pendant armature does not itself make contact, but ends at V in a trip lever which pushes lever T carrying contact surface S_1 forward enough to reset the lever N and then allows lever T to fall back. I understand, however, that this was not found beneficial and that they have since adopted the pure momentum break of the "Synchronome" system. The propulsion of the wheel is not shown, but it carries pins J, J_1 which, at the completion of revolution, raises the projection K on cranked lever F, centred at H, thereby allowing the lever G to ride at a lower level and disengage the hook M from the catch O.

The dial movement of the Gent system is also very similar to that illustrated in Fig. 7 in its earlier form; in fact, most uni-directional current systems have now adopted the electro-magnetic time counter described in the 1899 paper.

From the first inception of the "Synchronome" system in 1895, the dominant idea was to design these dial movements for quick action and the switch for slow action, giving the latter both mechanical and electrical inertia. The dials are made to work with less current and with a contact of shorter duration than is required to operate the switch, but it was obviously desirable to measure the extent to which the current rate and the duration of the contact exceeded in ordinary practice that required by the dials. And it is well to demonstrate in a convincing manner how short is the duration of impulse necessary, because nothing less than a whole second was previously used, and most systems of electric clocks on the Continent and in the United

States of America still have impulses whose duration is from fifty to one hundred times longer than necessary.

Thanks to Mr. Duddell's oscillograph, I have now been able to investigate the precise nature of the impulses transmitted by the "Synchronome" switch and exactly what happens in circuits of elec-

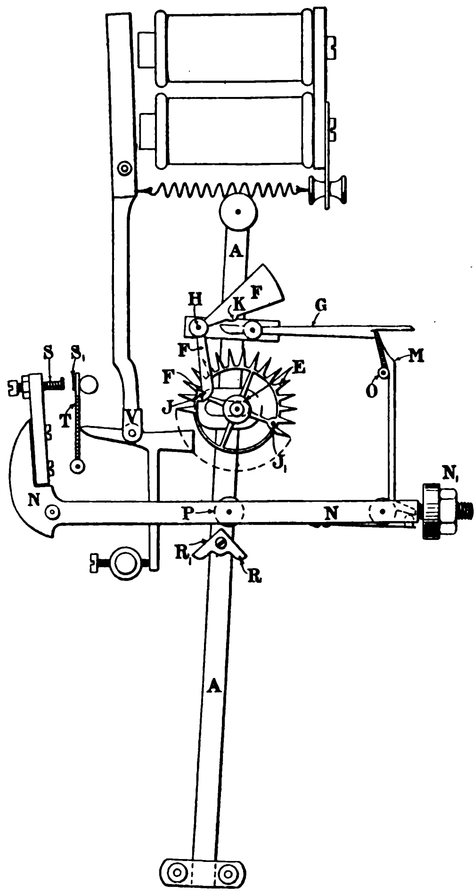


FIG 8.

trical impulse dials of varying number and size. The precision of the make and break has been demonstrated and compared with the intermittent nature of the mechanical or relay contacts previously used for such purposes. It has also been possible to determine precisely the most efficient arrangement of electric time circuits with regard to duration of impulses and voltage, and to lay down rules whereby full

advantage is taken of the compensatory effects of increased duration of impulses consequent upon decline of battery.

For the purpose of this investigation a "Synchronome" time transmitter of the type illustrated in Fig. 6 was used in series with various sizes and numbers of dial movements as illustrated in Fig. 7. An oscillograph was included in the series circuit so adjusted that a deflection of 40 mm. was produced by a current of 1 ampere. The wave-forms were recorded on partially counterbalanced falling photographic plates arranged so that the mean speed of the plates was 100 cm. per second. The plates were supported on a catch at the top of a light-tight slide and fell into a red cloth bag at the bottom. The catch was withdrawn by an electromagnet controlled by a contact on the pendulum set to operate about a second before the observation, the exact time being readily adjustable to allow for such variations as differences of weight of the photographic plates.

Out of a large number of wave-forms recorded, sixteen are selected for reproduction, and they will serve to show most of what is to be learnt from the investigation. The arrows indicate the direction of the fall of the plates past the spot of light from the mirror of the oscillograph. The base line in each curve is, of course, the photograph of the spot before and after deflection.

No. 1 is the wave-form of an impulse of the transmitter alone with nothing but the oscillograph in circuit. The E.M.F. (three small dry cells) was 4·2 volts, and total resistance 9·46 ohms. The full value of current, 0·44 ampere, was not reached until 0·05 second $= \frac{1}{20}$th of a second. At 0·06 of a second as the armature approaches the poles of the magnet with considerable velocity the back E.M.F. begins to reduce the current, which drops to 0·35 ampere when the switch lever is thrown off by its momentum.

The precision of the make is worthy of special notice. It is due mainly to the switch arm "sailing" into contact at the speed of the moving pendulum. The best speed was determined by experiment, and it is easily adjustable by (*a*) moving the switch vertically up and down the pendulum rod, (*b*) varying the arc of the pendulum, or (*c*) varying the point in the excursion of the pendulum from left to right at which contact was made. It is the more remarkable in the conditions of low resistance and low voltage where variations of contact resistance would make the oscillograph mirror dance if any ordinary contact device were used. I have not yet been able to determine the precise moment at which the armature begins to move, but it seems safe to say that the devotion of the whole of the electro-magnetic energy to pulling it into harder contact has something to do with the freedom from any trace of intermittency.

If the gravity arm is allowed to travel into contact too quickly, and if the leather buffer is removed from the armature-field limiting screw, a "bounce" will occur as shown in wave-form No. 2. The preliminary false impulse is, of course, insufficient both in current value and in duration to affect even the most sensitive dials, but even such trivial

intermittency is undesirable, and it is a satisfaction to know that under normal conditions it cannot occur.

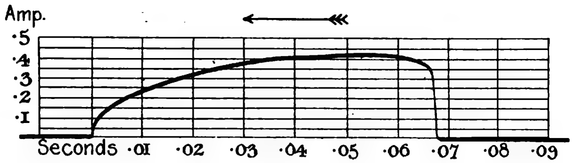
The break of all the impulses whose wave-forms are here reproduced is practically instantaneous, or at any rate so quick that the photographic plate can hardly record it. This is the natural result of the armature being stopped dead against the poles of the magnet whilst the lever is free to fly off on to its retaining catch. The area enclosed by the curve is, of course, the measure of the current consumed. An average of 0·35 ampere × 0·066 second = 0·023 coulomb, and that × 120 × 24 × 365 ÷ 60 ÷ 60 = 6·7 ampere-hours per annum.

No. 3 is the wave-form of an impulse with one small dial movement (as used for a 12-in. clock) in series with the transmitter. One cell was added to keep the current rate nearly the same, the figures being 5·6 volts, 13·62 ohms, and 0·41 ampere. The dial has operated on 0·3 ampere after the circuit has been closed for 0·015 or $\frac{1}{68}$th of a second, a fact that is revealed by the back E.M.F. set up on the completion of its armature stroke. This clearly proves the unnecessarily long duration of the impulse, but when the tension of the steel spring of the dial movement was strengthened it required another $\frac{1}{10}$th ampere and $\frac{3}{100}$th of a second to operate it.

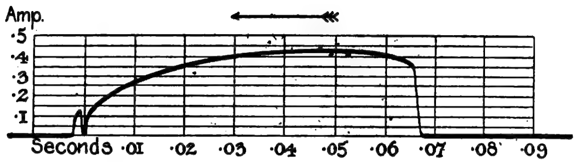
The effect of adding this dial without an extra cell is shown in wave-form No. 4, in which the figures are 4·2 volts, 12·62 ohms, and 0·33 ampere. The current did not rise to the 0·3 necessary to work the dial until the switch had been closed for 0·04 or $\frac{1}{25}$th of a second, and the total duration of contact was 0·1175 or nearly $\frac{1}{8}$th of a second. Thus by fixing the current necessary to work the switch at a higher value than that required to operate the dials, the former cannot work at all without transmitting sufficient energy to operate the latter, the same margin for safety being maintained throughout the fall of voltage, so that if there is sufficient electrical energy available to work the switch, the dials are bound to work. The area enclosed by curve No. 4 is 0·036 coulomb = 10·5 ampere-hours per annum, so it is obvious that the higher the voltage the less current will be consumed, because of the difference in the duration of contact. We see from wave-form No. 4 that the switch will operate with $\frac{1}{10}$th ampere less than in wave-form No. 3, but takes nearly twice as long to do so. The two moving members of the switch travel at half the speed, but the distance covered is the same, and the apparatus is so designed that the acceleration is still sufficient to effect the break by the momentum of the lever, and to throw it on to its catch again with any current just more than sufficient to operate the dials.

In these first four wave-forms the self-induction is small relatively to the mechanical inertia of the switch. Consequently the current has time to rise to its full value, and in the last one remains at its full value for quite a long time ($\frac{1}{15}$th of a second) because it is only just sufficient for the work.

Self-induction having been considered an enemy in other systems, let us see its effect and why we can now welcome all the electromagnetic inertia that our instruments possess.



No. 1.



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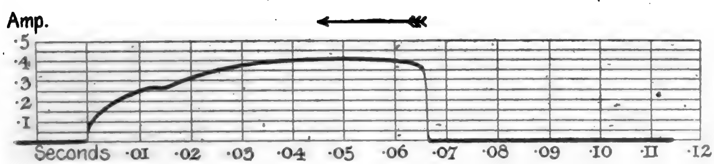
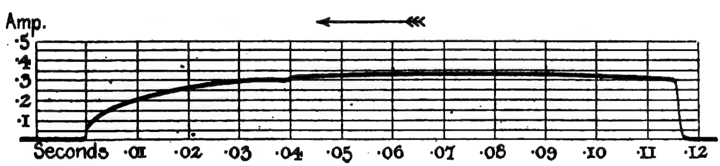


No. 3.



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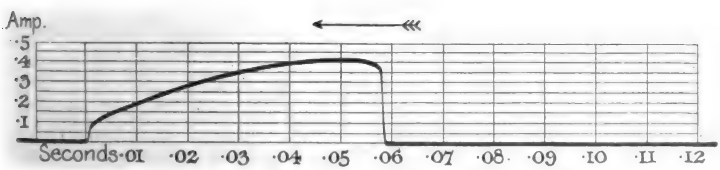


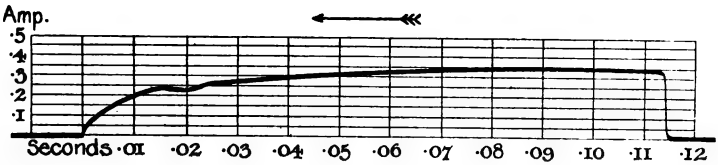
No 5.

Wave-form No. 5 is almost the same as No. 1 and should be compared with it, but with the electromagnet wound to a higher resistance to increase the self-induction and the armature field limiting screw brought forward (turned in) to reduce the work to be done. The transmitter alone is in circuit with the oscillograph, and the figures are 4·05 volts, 8·73 ohms, 0·46 ampere. The increased self-induction is seen in the slower rise of current, and the switch completes its functions, and the circuit is broken again before the current has risen to the full value (0·46) which it would have attained if time had permitted or the work to be done had required it. The area enclosed by the curve is 0·017 coulomb, or 4·97 ampere-hours per annum, the less consumption being, of course, due to the fact that the gravity arm does not fall so far, and the armature has consequently a shorter distance to lift it.

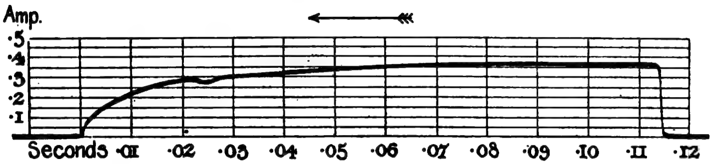
The next three wave-forms illustrate impulses through circuits of (No. 6) twelve small dials, (No. 7) thirty-six small dials, and (No. 8) thirty-six small, ten large, and two turret clocks. In each case the voltage was increased proportionately so that a uniform current rate of 0·42 ampere would be developed if the switch remained closed long enough. But 0·35 ampere being sufficient, and the self-induction of the circuit being so considerable that the current increases throughout the period of closed contact, the break always occurs at that figure. It will be observed that the dials operate at 0·25 ampere, and the effect of the added self-induction is clearly seen in the longer time required for the current to rise to that value. A circuit of twelve small dials takes 0·02 ($\frac{1}{50}$) second, thirty-six take 0·025 ($\frac{1}{40}$) second, while forty-eight dials, including some larger turret clocks, take nearly 0·05 ($\frac{1}{20}$) second.

For the last three wave-forms the armature field limiting screw of the switch was backed out in order to ascertain to what extent the duration of the contact would be prolonged by increasing the travel in company of the two members of the switch, but in wave-form No. 9 this is restored to normal in a circuit comprising twelve small movements and two large ones, having a total resistance of 61·8 with E.M.F. 23 volts, and current 0·37 ampere. The area of the curve is 0·012 coulomb = 3·5 ampere-hours per annum. The dials operate at 0·25 ampere in 0·045 second, and the switch breaks at 0·27 ampere in 0·06 second. The voltage might decline to 16 (a drop of 30 per cent.) or 26 ohms resistance might be included in the circuit (an addition of 42 per cent.) before the magnet would refuse to reset the gravity arm. But the duration of the impulse would be two or three times as long.

This compensation for drop of voltage and rise of internal resistance of battery is more than we need for securing safe going of the dials, but it is most useful as a means of indicating impending failure of battery because the difference in the duration of contact is so marked that it can be demonstrated visually or audibly—for instance, by means of an electric bell whose hammer is balanced so



No. 6.



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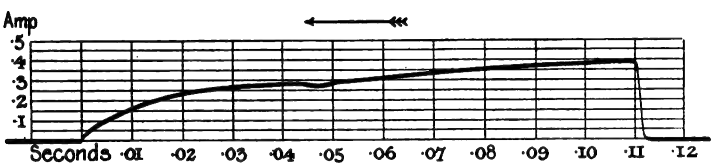

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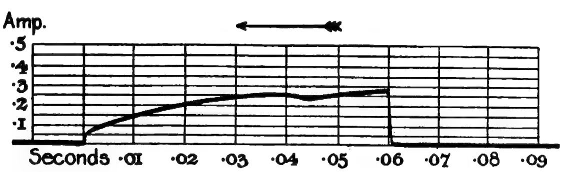

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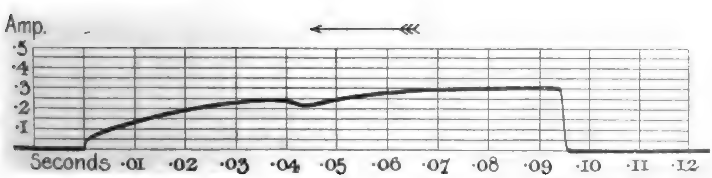
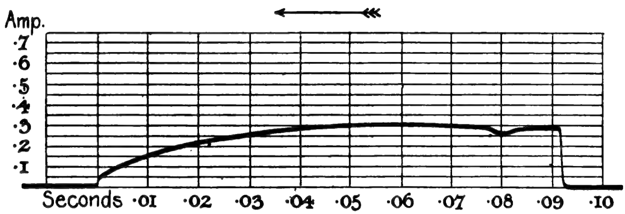


No. 10.

that it only rings with long contacts. But the most effective battery warning is the sudden increase in duration to a whole second which occurs when the current is insufficient to operate the switch though still enough to work the dials. The switch then remains closed until the pendulum on its return swing assists the magnet to replace the gravity arm on to its catch.

A difference of efficiency as between dial and switch of only 0·02 ampere is rather a small margin. Current is cheap, and we would like our switch to remain closed more than 0·015 second longer than the



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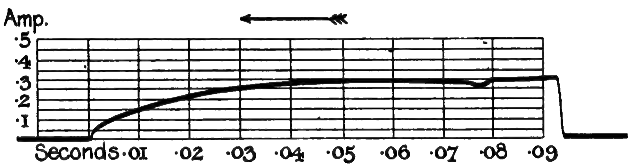

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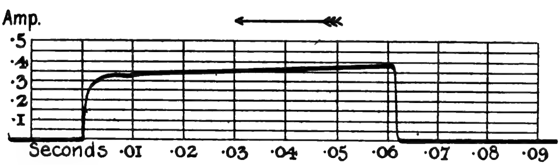


No. 13.

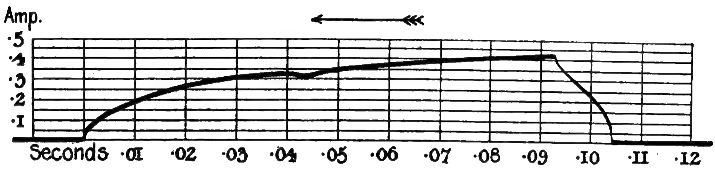
dials in case one of the latter has had its spring left unnecessarily strong by a careless workman, so we backed out the armature field limiting screw again one revolution (0·024 in.), with the result (shown in wave-form No. 10) that the duration is increased by $\frac{3}{100}$ second and the current by 0·05 ampere.

The tension of the springs of all the dial movements were then considerably increased. As will be seen in wave-form No. 11, they require 0·3 ampere to operate them, a current rate which is not attained until the circuit has been closed for 0·08 of a second.

The effect of increasing the tension of the armature tail-spring by

three revolutions of its screw (0·072 in.) is shown in wave-form No. 12 to increase the margin by $\frac{1}{200}$ of a second.

That the inertia of the dial armatures cannot be ignored is demonstrated in wave-form No. 13, in which the circuit comprises the switch and twelve small dials as in curve No. 6, but the current is taken from the lighting mains at 204 volts with a 32-c.p. 200-volt carbon filament lamp in series. The beginning of the curve is steep owing to the voltage being high and the self-induction trivial compared with the non-inductive lamp resistance. Though these dials will work on 0·25 ampere if they have 0·02 of a second to do it in, the current has to



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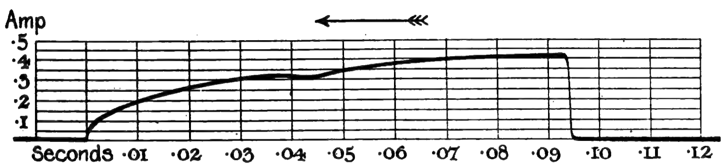

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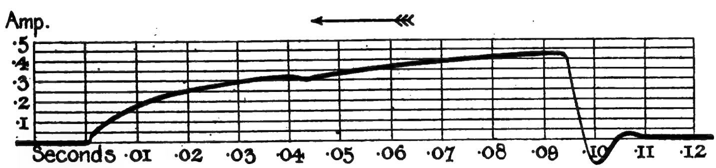

No. 16.

rise to above 0·3 to accomplish the work in half the time, and any attempt to work them more quickly would involve a much higher voltage, and it would be undesirable on account of the noisy action of the dials that it would cause. On this ground also self-induction is welcomed, and one of the reasons for arranging time-circuits in series is that we may have its sum. It will be noticed that the curve rises in a straight line from 0·35 to 0·4. This is due to the lamp filament warming up and reducing its resistance. If the switch had not then had enough it would rise to 5·8 amperes, and when lighting mains are used the lamp selected should have a filament of such resistance that the dials operate in that rise.

We can now lay down some general rules which will be applicable to all time circuits controlled by a "Synchronome" switch.

The switch magnet should be wound with that number of turns which will just fail to enable it to work on the current rate which will work the dials.

The mass of the two moving members of the switch and their travel in company must be sufficient to endow it with the ordinary qualities of a reliable switch, yet small enough to enable the break to occur very shortly after the dials have operated within the time constant of the circuit, and before the current has risen to its full value.

If this is done full benefit will be obtained from the compensatory action, which is of such value when primary cells are used as the source of supply.

The voltage should be well above that required to produce the current rate necessary to operate the switch. The only objection to excess is noise, and the more you have the greater is the margin of safety and the less is the consumption of current.

A bad spark at the break is shown in wave-form No. 14 with all dials in circuit. No. 15 shows the effect of shunting the magnets with a non-inductive resistance, and No. 16 shows the effect of shunting the contact with a condenser of $1\frac{3}{4}$ microfarad capacity. The rebound of the latter should be useful to dispel residual magnetism. It can be safely used because its value in time and current is altogether too small to amount to a false impulse.

It should be noted that all the variations in the stroke of the armature carried out for the purpose of investigating their effect upon the electrical impulses had no appreciable effect upon the timekeeping of the pendulum. The weight of the gravity arm is 14 grammes, and its normal fall is $4{\cdot}75$ mm. $\times 120 \times 24 \times 7 = 1{\cdot}34064$ kilogram-meters $= 9{\cdot}7$ ft.-lbs. per week. This is sufficient to keep a seconds pendulum with 12-lb. bob vibrating with an arc of $1\frac{1}{4}°$ on each side of zero. We varied the fall of the gravity arm by about 12 per cent., and in doing so we varied the amplitude of the vibrations of the pendulum accordingly, but only within limits in which the effect of the circular error is practically negligible, and the impulse is concentrated as far as possible at zero, whilst at the same time vibration is avoided by curving the impulse pallet instead of making it a straight slope at an angle of 45°. The idea is that the impulse shall begin with extreme gentleness, increase rapidly to a maximum at zero, and diminish in identical ratio.

Fig. 9 shows a curve of mechanical force in which the base line A E is assumed to represent the path of the pendulum, a distance of $\frac{3}{4}$ in. at a point 13 in. below its suspension. From A to B the pendulum swings in free air and touches nothing. It then moves the wheel, and on the occasion of its fifteenth excursion from left to right it also accomplishes the release. It performs these functions when its velocity is almost at its highest and its kinetic energy also its greatest. The impulse now begins, gently at first, but with rapidly increasing force, the vertical

elevation of any point on the curve being the measure of the horizontal driving force at that point of the pendulum's path. At C, when the pendulum has arrived at zero it is at its maximum; after that the impulse declines in strength until it dies away altogether at D, the whole operation having taken place in a space of $\frac{3}{16}$ in., being one-quarter of the total travel of the pendulum and a period of one-eighth of a second. The curve G F above gives us the shape of the pallet required,

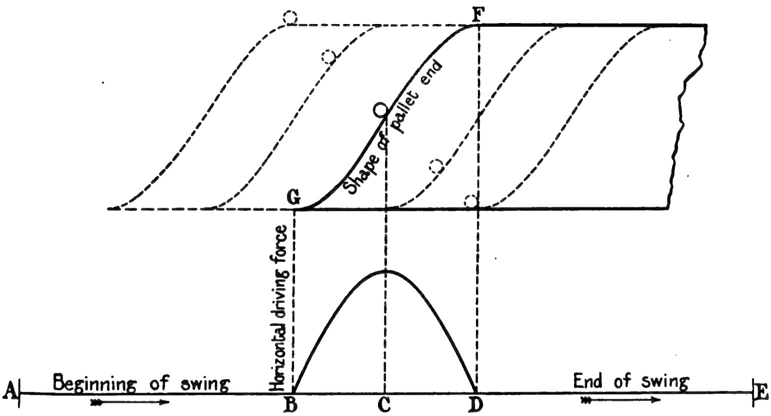

FIG. 9.

and is mathematically produced from the force curve; for as the angle of inclination of the impulse surface alters, so also does the resultant horizontal thrust.

We have seen that the smallest curve illustrated has an area of 0·012 coulomb = 3·5 ampere-hours per annum, and the largest about 0·36 coulomb = 10·5 ampere-hours per annum, and that they can be greatly reduced if desired without fear of the break occurring before the dials have had enough current. At 1-volt drop per dial, which is ample for all ordinary sizes for interior use, the consumption of current should not be more than 3·5 watt-hours per dial per annum, this low figure being due to the small contact time factor of only ten hours per annum. Now if we are using a primary battery we cannot hope to get out of it any reasonable amount of energy during its natural life if we have only ten hours in the year in which to do it. We have seen the great advantages of arranging time-circuits in series, and it is impracticable to increase the discharge rate much further; consequently we shall not achieve much economy by shortening the impulses, nor is it particularly desirable. It is true that 1 watt-hour (equivalent to 2,654 ft.-lbs.) should be ample to run a clock of this size for twelve months, and that a good dry cell is capable of yielding, say, 100 watt-hours on a suitable load in a suitable time, and should therefore run, say, 33 clocks for three years. It cannot do so because the energy it

contains, though sufficient in measured units, is not in a form suitable for expenditure on the work in hand. No such degree of efficiency is possible in any system which uses current for so short a period, yet the balance of convenience in other respects is entirely in their favour.

Brief mention should be made of two more systems which have appeared since 1905—Bowell's and Murday's. The vibrations of the pendulums of the master clocks in each of these systems are maintained by the Foucault-Hipp electric "Butterfly" escapement illus-

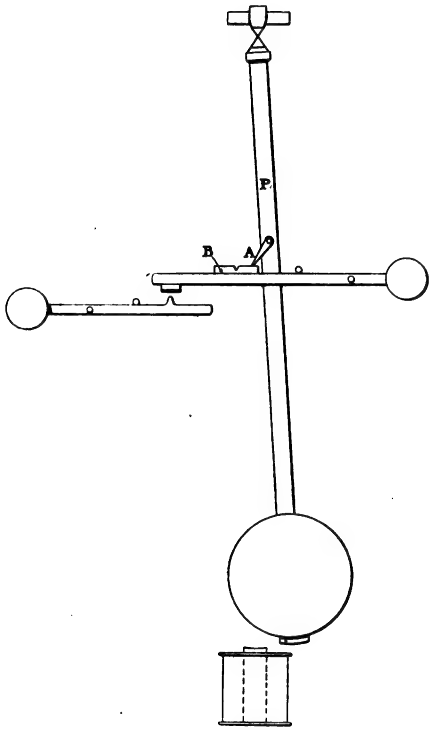

Fig. 10.

trated in Fig. 10. The little trailer A pivoted freely on the pendulum P swings clear of the notch in the block B until the arc falls to a certain predetermined minimum, when it jams in the notch and presses the two counterbalanced levers together, making a reliable contact and causing the magnet below the pendulum bob to restore the arc.

In both systems a count-wheel is used to select the semi-vibration at each half-minute when contact shall be made for the operation of the dials.

In G. B. Bowell's system (made by the Silent Electric Clock Com-

pany) the pendulum charges into contact springs at the end of its swing, making a comparatively long contact to operate dial movements with rotary armatures in a permanent magnetic field.

In T. J. Murday's system (made by the Reason Manufacturing Company, Ltd.), the contact is a passing one made at zero, and the dial movements have reciprocating armatures pivoted between the poles.

For twenty-five years Mr. Murday has been the principal exponent of the Hipp Butterfly escapement in this country, and had made many useful and original applications of it. In 1901, with the Standard Time Company, Ltd., he applied it to the heavy pendulums of turret clocks with perfect success and inaugurated a method of turret clock driving which has a great future before it.

Looked upon simply as a method of conversion of electrical energy, this is probably the most efficient motor ever designed, and it must be

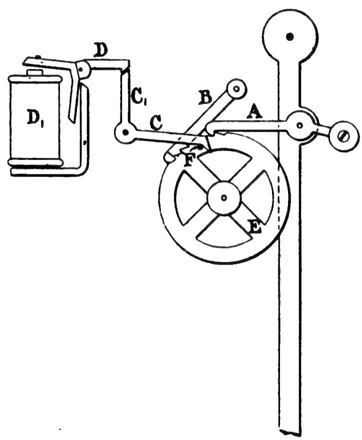

FIG. 11.

remembered that, unlike ordinary motors, it is at its greatest efficiency when working at its slowest speed, rotating its driving wheel at the rate of, say, 1 rev. per minute. There is no theoretical limit to the amount of power which may be developed by this means, and it increases the frequency of its impulses automatically in exact proportion to their lack of strength and in proportion to the work demanded of it.

By the addition of a third contact lever below the other two the Standard Time Company provide an alternative source of electrical energy which comes into operation if the first one fails. Gents, of Leicester, have recently introduced a simple means of bringing a Hipp-driven clock under the control of a half-minute time circuit, similar in principle to that used by the Standard Time Company for synchronising it. It is illustrated in Fig. 11. In vibrating

the pendulum pulls round the wheel E by means of the hook-shaped pawl A. The length of the pendulum or the number of teeth on the wheel E are so arranged that the hands of the clock are advanced half a minute in about 27 seconds by means of this gathering pallet A. A pin F in the wheel E then lifts the control lever C and disconnects the pawl A by lifting it out of the wheel E and allowing the pendulum to oscillate idly. When the half-minute time-circuit impulse energises magnet D_1 the arm C_1 of lever C is released and the pendulum again drives the hands as before.

There may be some limit as to the size of a turret clock which can be dealt with by this method, and I offer a constantly running motor controlled by a "chaser" switch as being suitable for the "Big Bens" of the future.

A motor with a double-worm reduction gear, reducing the speed from, say, 1,800 revs. per minute to 1 revolution in 5½ minutes, carries a disc rheostat on its slow-moving axle. A switch arm mounted freely on this axle is driven by an electrical impulse dial movement in a standard time-circuit of half-minute periodicity on to the contact studs, cutting out resistance in the motor or armature field. These resistances are so proportioned that the motor is constantly running at a speed dictated by the half-minute progression of the chaser switch.

Existing turret clocks may be relieved of their dangerous and cumbersome driving weights and the necessity of winding them (which often has to be done daily) by means of small rotary motors. The Huyghens endless chain is admirably adapted for the purpose of connecting a motor to the "going" train of any ordinary turret clock. All that is wanted is bicycle gear-wheels and chain supporting a small weight which switches the motor in at the bottom of its fall and out at the top. Bell hammers may be directly driven without the intermediary of any *remontoir*.

It is satisfactory to note a recent tendency to more enlightened inventive work in this field—really progressive improvement based upon such of the work of other inventors as has been proved to be sound.

The experience of the last ten years has shown that the principles then formulated before this Institution are necessary to the success of any system of electrical impulse dials with simple movements for operation by uni-directional currents. The most important of those principles were the transmission of energy through the surfaces of the contact and taking it from the electromagnet instead of from the clock or its pendulum; the immense economy of current and the certainty of its sufficiency obtained by short duration contacts dictated by the self-induction of the whole system; and the momentum stop in the dial movement.

Since then the application of Sir Henry Cunynghame's free detached gravity arm and the extended range of battery warning given by the pendulum's assistance to the magnet in resetting the switch have given a great impetus to electric time service.

Circuits of electrical impulse dials will always take the premier position as the most generally useful application of electricity to horology because that method is the most simple and direct means of attaining absolute uniform time with a high degree of accuracy. Now that we have succeeded after so long a fight in breaking down the prejudice aroused by the failures of so many systems, let me urge manufacturers and contractors not to kill the goose that lays the golden egg by cutting prices and by putting in electric-bell wiring.

I have always claimed for electric time service a position as a reputable branch of our profession, and I can do so with more confidence now, thanks to the enterprise of other firms who have taken up the business of electric clocks and the healthy competition which has resulted.

ADDENDUM.

(*From Information supplied by various Makers.*)

The Aron Electricity Meter Company, Ltd.

The chief electric clocks manufactured by this company are the self-contained and the synchronised clocks, the latter consisting of one master clock and several sub-clocks or dials. The self-contained clocks and the master clocks may be perhaps more correctly described as "electrically wound" than "electric," for, except in so far as the winding is performed electrically, they are identical with the familiar hand-wound clock. The electrical winding is effected by means of a special winding gear which can be arranged to work off any supply, from, say, a single dry cell up to the highest power or lighting circuit, whether direct or alternating current. The author's description of the self-winding action on page 52 is correct, but Fig. 12 should be substituted for his Fig. 2, because it shows a later pattern of armature B and spring C. The reference letters are the same, and the action will be easily understood. The self-winding occurs about every 10 minutes and occupies only a fraction of a second, being practically instantaneous. By means of suitable ratchet wheels and clicks the centre arbor can only rotate in an anti-clockwise direction, that is, with the unwinding of the main power spring. It is to be specially noted that the making and the breaking of contact take place at different points on the pin as well as on the plate, the pin always rolling along the plate thus ensuring a clean contact. The Aron master clock for driving sub-clocks does not depart from the standard clock mechanism, as the alterations of the vital parts of the clock, attempted by various electric clock-makers, have proved to be failures; this is hardly remarkable, considering the high state of efficiency to which timepieces have been brought during many hundred years of

development. An ordinary regulator pattern clock is employed with additional gearing for actuating the contact arrangement. The clock and this contact gearing are connected to a differential gear which is driven by the above described winding gear.

Fig. 13 is a diagrammatic representation of a master and sub-clock circuit. As the author says, this system works on the polarised "receiver" principle. The flow of current in the master clock transmitter has therefore to be reversed every time the receiving dials are pushed forward. For this purpose the contact segment (5) is geared to a fan escapement which is actuated in a similar manner to that of a

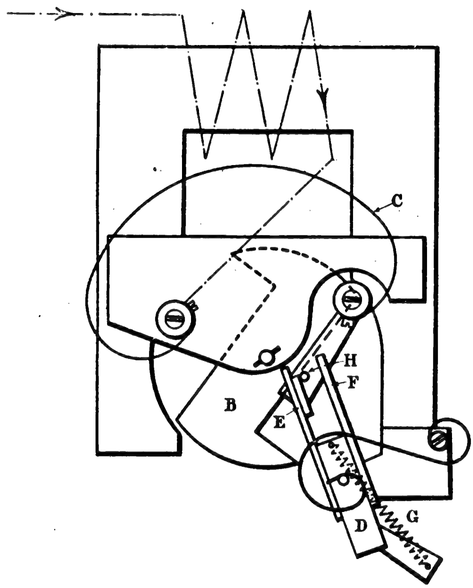

FIG. 12.

striking mechanism. At regular intervals the fan escapement is released, which results in the revolving of the contact segment one-half of a revolution in a clockwise direction when it again comes to rest, this operation taking about 1 second. In making this half revolution it will be seen that the segment first lifts the brush (8), breaking contact between (8) and (6), and then makes contact with this brush, sending an impulse through the dials or sub-clocks, the return circuit being easily followed by reference to the diagram. On rotating further the contact with the brush will be broken, and the segment comes to rest in the dotted position shown in the Fig., where it will remain until it is again released. It will then again rotate half a revolution in the same direction, first lifting and breaking contact between (9) and (7), and then making contact with (9) sending an impulse in the reverse direction through the

sub-clocks, afterwards breaking circuit and coming to rest in its original position. Here again, as in the winding gear, contact is made at a different point from that of the break (make at 10, 10*a*, break at 11, 11*a*), thereby ensuring always a clean contact. The receiving dial has a U-shaped electromagnet to which is fixed a permanent magnet, the one pole (12) being near the fulcrum of the soft iron anchor (13). By reversing the current in the electromagnet the anchor is rocked to and fro. The pins fixed at the ends of the anchor engage into and drive the escapement wheel (14), the teeth of which are so shaped that at the end of each stroke the wheel is perfectly locked. From the escapement wheel motion is transmitted to the minute and hour hands of the dial in the usual manner. For large

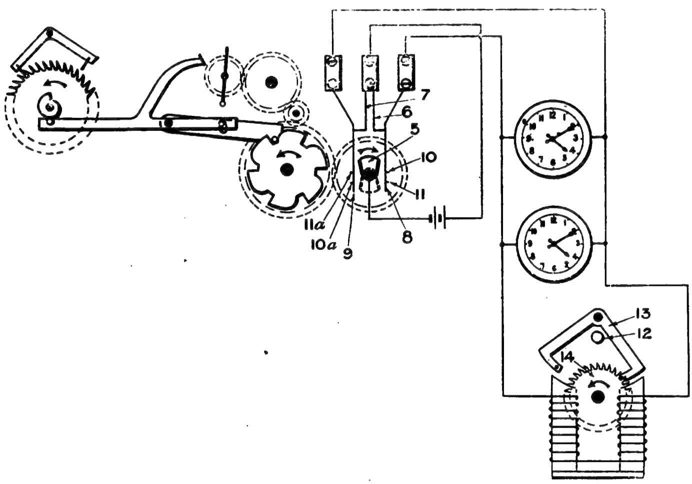

Fig. 13.

installations several secondary master clocks are employed, and they are regulated periodically to a second by one master clock which can be synchronised to Greenwich time. As a general rule, the master and the sub-clocks are driven from dry batteries with the sub-clocks in parallel, but if desired they can also be constructed for any direct-current voltage.

Gent & Company, Ltd.

The pattern of Gent & Co.'s master clock or transmitter described by the author, and shown at Fig. 8, page 62, is only employed by the makers when a centre seconds transmitter is desired.

The pattern more generally installed is shown at Fig. 14, in which the same principles are retained but the seconds indication and the subsidiary contact trip lever are dispensed with. The modifi-

cations will be readily understood by reference to Fig. 14, and the action is similar to that described in respect to Fig. 8, except that when the release of the gravity arm is accomplished by the pendulum on its swing to the right, the roller falls on the dead face of the pallet and gives the impulse by rolling down the inclined surface during the return swing of the pendulum to the left.

Our warning bell is shown in Fig. 15. It is silent so long as the duration of the contact is normal, but on the duration being lengthened by the action of the pendulum assisting the gravity lever as above

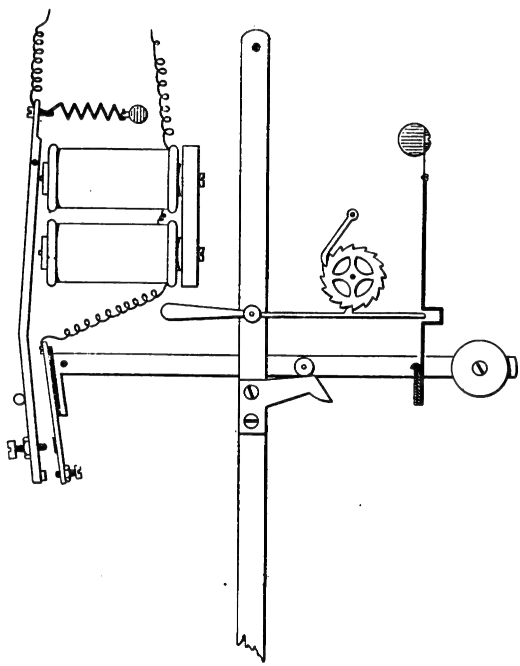

FIG. 14.

described, it sounds one blow at each half-minute. Its mechanism is very simple. It consists, as will be seen, of an electrically operated swinging counterpoised hammer containing sufficient inertia to prevent its operation with impulses of short duration, while permitting its operation with impulses of long duration.

Locked Impulse Movements.—Illustrating the advance made in movements of this class it may be pointed out that ordinary locked movements as illustrated by the author are liable to jamb when forward pressure is applied to the minute hand, such as for instance by wind, due to the vice-like grip exerted on to the driving pawl by the engaged

tooth of the wheel on the one side and the fixed stop on the other. To obviate this defect Gent & Co. have introduced a series of movements in which the action is locked on the principle shown in Fig. 16. In this movement the stop of the driving pawl moves back with it on being withdrawn from the tooth, thus obviating the vice-like grip.

The action of this movement is as follows: While the click U is being drawn along the face of the tooth which it engages, the wheel V remains locked by reason of the armature lever carrying the driving click being pivoted at right angles to the tooth's face. On the click falling and engaging the next tooth, the roller W holds the backstop click X in engagement with the wheel, and its curved extension permits the backstop click to rise only as the forward movement of the tooth which it engages demands. A number of these movements are in operation driving the exposed hands of turret clocks in exposed

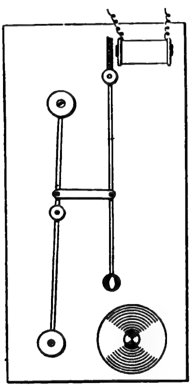

FIG. 15.

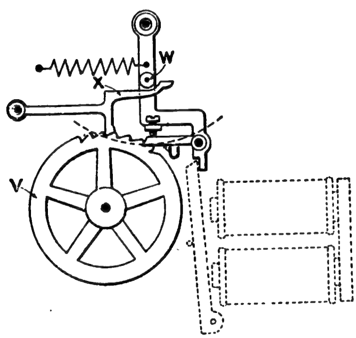

FIG. 16.

positions and are unaffected by wind and storm. These movements are also employed for operating workmen's check clocks.

Turret Clock "Waiting Train" Type.—The pendulum similar to Fig. 11 is not a timekeeper, but simply an oscillating motor, and its duty is to pull round an escape wheel E, by means of the hook-shaped pawl A, tooth by tooth. The arbor of the escape wheel E carries a worm which drives a wheel, and which can be geared into four hand spindles for a four-faced clock, or one for a one-faced clock, as may be desired.

On the vibrations of the pendulum falling to a certain minimum value a Hipp-contact device closes a local battery circuit, and an electro-magnet mechanically re-energises the pendulum. This mechanical re-energisation is distinct as from the usual magnetic re-energisation communicated to a pendulum fitted with the standard form of Hipp-contact. This re-energisation is conveniently communicated to the pendulum, and takes place in direct proportion to the work to be done.

Under normal working conditions, re-energisation takes place about once per minute, but on heavy work being thrown on to the movement due to resistance of wind pressure on the hands the pendulum becomes energised more often; each complete vibration if necessary. On being energised at each complete vibration the motor then develops fifty times its normal power, and it is impossible to stop the movement by hand, even when exerting one's full power on to the work wheel. A number of these movements are in operation driving large turret clocks having dials of various sizes, one clock having four dials each 10 ft. in diameter which are driven by one movement only. The action of the control has been ably described by the author on page 74.

The "waiting train" system of half-minute control obviates the necessity of any separate controlling device or circuit, the magnet D of the control relay being placed in the impulse circuit just as an ordinary dial movement.

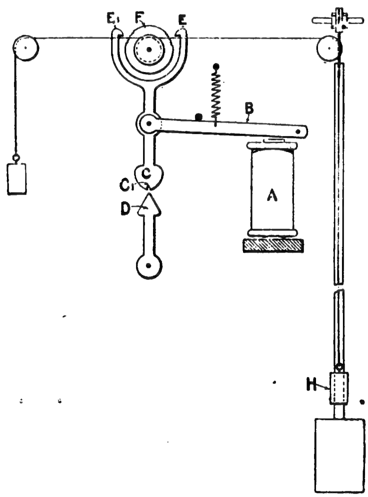

FIG. 17.

Electrical Distribution of Time over Large Areas.—In many installations of electric clocks it is undesirable to arrange the whole of the clocks in one series circuit when the number of clocks is large or when the circuit contains overhead risks. A better method is to arrange the clocks in groups, each group being driven by a separate transmitter or master clock. In order, however, that the time may be nevertheless uniform the separate transmitters are all controlled by a master or prime transmitter in the following manner:—

It is arranged that the prime transmitter sends hourly controlling impulses to each of the separate or sub-transmitters which impulses operate automatic regulators which are connected to the pendulums of such transmitters. These regulators automatically move a regulating

weight up the pendulum rod if the transmitter at the hourly impulse is found to be slow, and down if found to be fast, and further the weight will even take up a new position when required by changes in the condition of oil or by other disturbing influences, a distinctive feature being that the regulator will find its correct or required position, and will remain there until an alteration in the rate of the pendulum again takes place. It will be seen that this system of time distribution known as the Ball-Parsons is not a system of setting or temporary correction but a system of automatic regulation, one of the many advantages being that in the event of, say, an overhead wire becoming disconnected by storm the sub-transmitter and group affected by the disconnection would have been regulated up to the last hour and would keep uniform time with the other groups for a long period in the absence of the control, and on again being brought under control, its accumulated error, if any, would become automatically corrected.

Fig. 17 shows diagrammatically an arrangement of the control. The magnet A on receiving an hourly impulse pulls down the armature B and with it the feeler C on the point D, which is rotated by the sub-transmitter and which should be perpendicular at each hour. On the feeler C finding the pointer D slow its lower end becomes tilted to the right and its upper end to the left and the pawl E then engages the ratchet-wheel F, which winds the regulator H up the pendulum rod. This action would be repeated at each hour until the sub-transmitter is brought up to time. The reverse action will then take place, and after one or two oscillations of the regulator H it will finally be left in the required position. So long as the sub-transmitter is indicating correct time, the notch C_1 of the feeler C engages the point D and no regulating action takes place.

The Reason Manufacturing Company, Ltd.

The contact applied to the intermittent driven pendulum and commended by the author as being made at the zero position is illustrated in Fig. 18, which shows a light brass fitting clamped on the pendulum rod. This fitting carries a substantial cylindrical silver pin, which passes, at every swing of the pendulum through the vertical, between two similar pins fixed on the ends of two flat German silver springs. By means of adjusting screws a greater or less tension may be given to the springs. An ebonite knob acts as a distance-piece and prevents the pins from touching each other. It will be understood that the pin on the pendulum, as it forces its way between the spring pins, completes the electric circuit for a fraction of a second; while at the same time the mechanical rub between the cylindrical surfaces serves to keep the contact bright and clean. A threaded brass pillar, secured to a brass base plate, carries the ebonite block to which the German silver springs are attached. By means of back and front clamping nuts this block may be adjusted to any position of the pillar, so as to ensure the silver pins lying exactly in the line of the pin which is carried by the pendulum. The best position for this contact is about

one-fifth the total length of pendulum from the suspension point. The further down the rod it is fixed the shorter will be the duration of the contact and *vice versâ*. A duration of about $\frac{1}{25}$ of a second is most suitable for driving the mechanism of the secondary dials. The magnet of the centre seconds dial designed specially for work of this class is wound to a resistance of about 80 or 100 ohms, and works efficiently with a current of 0·03 ampere. Dry cells or small accumulators will run the circuit continuously for many months at a time without renewal or recharging. The whole fitting is designed so as to be easily attached to any regulator without necessitating the taking down of the pendulum—one part being simply clamped to the pendulum rod by two screws and the other part screwed to the back of the regulator case.

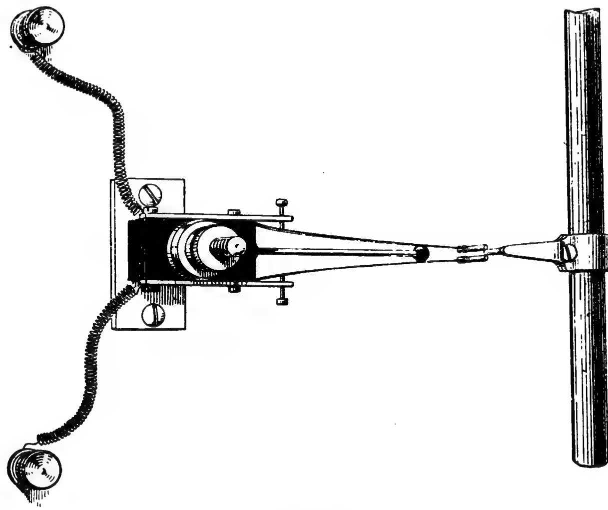

FIG. 18.

The New Balance Wheel Electric Clock.—This consists of a large and heavy balance wheel electrically operated on a somewhat similar principle to the pendulum in the clocks already described. The balance wheel drives the wheel train—not *vice versâ*, as in a spring-driven clock or watch. When the arc of oscillation falls to a certain fixed minimum the electric circuit is automatically closed and fresh energy is imparted to the balance wheel by the action of an electromagnet and armature sufficient to keep it vibrating for an interval of about two minutes—more or less according to the condition and strength of the battery. As with the pendulum operated on this intermittent method, the time-keeping is practically independent of variation in battery power. The balance wheel is made of a special nickel steel alloy which is unaffected by changes of temperature, and thus does away with the complicated con-

struction of a compensated wheel rim. The hardened steel pivots of the balance wheel staff or arbor are running in large sapphire cups, the friction being almost nil. A regulator arm is provided which acts on the giant controlling hairspring exactly as in a watch. By means of a roller attached to the upper part of the staff a lever is made to operate the wheel train at every oscillation of the balance wheel. This action is particularly safe and almost silent.

The Magneta Time Service Company, Ltd.

As the magneta time system is fundamentally different from other forms of electric clocks, and because it constitutes a method of working which has not previously been laid before the Institution, some of the chief characteristics which are only lightly touched upon in Mr. Hope-Jones's paper are here amplified.

The magneta master clock may be regarded as a dual piece of mechanism, wherein the two component parts for time measuring and electric impulse generating respectively are rigidly mounted on one plate or frame and constitute a self-contained controller. In the magneta controller the pendulum is left free to exercise its function of time measuring without encumbering it with contact making. Moreover, following the practice of observatory clocks, it is weight driven, and thus kept in uniform oscillation; the best conditions for precision of time measurement are thus secured. On this, therefore, as a basis, the electric part of the system is developed.

The electric impulses being mechanically generated are always of precisely equal value, and no outside source of current of any kind is resorted to. These induced currents are set up in a closed ring, thereby abolishing contact points. The inductor resistance is considerable, so that line resistance, even although it may represent many miles, is negligible. The system of secondary clocks is run in simple series, and small dials of a few inches in diameter up to large ones of many feet are in the same circuit. In installations consisting of several hundred dials it is convenient to divide the inductor into sections, each section being connected to a group of dials in the various portions of the district or building to be served.

As regards space occupied, the electric part of the controller practically does not add to the size of the clock; for example, a magneta controller with a case of the ordinary upright design having a cross-section of about 16 in. by 10 in. is a type capable of actuating from 80 to 100 dials. Few separate buildings require more than this; but master clocks are made up to any capacity. It is an important point in general use that the secondary dials are not affected either by vibration or the nearness of generators or mains carrying large currents. These conditions are both present at the Royal Mint, which was one of the first buildings in London to be installed with the magneta system, and the result has been absolute precision in working from the day it was erected.

As regards transformations of energy, the magneta system of working has an exact parallel in a generating station feeding motors over a network; and in any special cases where required electric winding of the master clock can be added, for the efficiency of an electric time system is not based on the consumption of current, which, as pointed out, is so small as to be negligible.

Discussion.

Mr. Kempe.

Mr. H. R. Kempe: The author in the opening portion of his paper has referred to the efforts made in the past by Ritchie and others. To Mr. Ritchie, however, is certainly due the honour of being the pioneer of electric clock systems. One of the causes of failure of electric clocks up to the last few years has undoubtedly been the difficulty of maintaining batteries, and probably the success which has now been achieved is largely due to the invention of the Leclanché battery (the salvation of the domestic bell system). I have mentioned Mr. Ritchie as being the pioneer, but I must say, and I think with authority, that by no man have electric clocks been brought to such perfection as they have been by Mr. Hope-Jones. The author states on page 50 of the paper that nothing of importance in synchronisation has been achieved since he first referred to the matter ten years ago. The Post Office does not as a rule advertise, but I may say that it has done a very large amount of synchronisation in the last year or two, and is continuing to do so. Our chief reason for synchronising in preference to adopting electrically driven clocks is because we have a very large number of clocks in various offices, which it would hardly be economical to scrap for the purpose of putting in electric dials. The synchronisation system adopted is extremely simple, costs little, and so far, has answered perfectly. In comparing synchronised with electrically driven clocks, it must be borne in mind that in the latter the hand moves every half-minute or every minute, whereas in the case of a spring or weight-driven clock the hand is continually going, and to set a watch it is only necessary to compare it with the hands of the clock. In an electric clock one has to wait till an impulse comes, and one is not certain whether it is the commencement or termination of the minute.

The necessity of keeping contacts clean is an extremely important point, having a very great bearing upon the success of electric clocks. Now Mr. Hope-Jones has casually alluded to the use of non-inductive shunts, but I think we ought to make more of that point. It is really extraordinary that although non-inductive shunts have been largely used in telegraphy for years, with only one or two exceptions, the manufacturers of electric clocks do not seem to have heard of them. A non-inductive shunt applied to a magnet completely extinguishes the spark, and contacts will work for a very long period without the slightest trace of oxidation. On page 54 the author referred to the trouble which a system sometimes undergoes owing

to the lack of expert handling. There is no doubt but that is a very important point. No matter how expert a mechanic may be, if he is put on work to which he is not accustomed, the chances are that when he tries to put a bit of mechanism right he does exactly the reverse. It seems therefore that in all mechanism of the kind it is extremely important that the adjustments should be as few as possible. It is often the custom to put in an adjusting screw here and there, with the notion that it renders the adjustment of the clock and keeping of it in good order very much easier. In most cases it has exactly the reverse effect. A mechanic who is put on to a clock which he does not understand will interfere first with one screw and then with another with disastrous results. If a clock is properly constructed and the frame is made firm, many of the adjustments might be absolutely permanent. I would go so far as to allow a workshop adjustment, but when an instrument is once put right in the workshop the adjustment should be firmly fixed. Even the application of the soldering iron would be an advantage, so that when the uneducated mechanic is employed he cannot possibly put the clock wrong. The author has referred to a system devised by Wheatstone in 1845, which was used in the Houses of Parliament and the Royal Institution of Great Britain. As a matter of fact, I was engaged by the British Telegraph Manufactory, which was started by Sir Charles Wheatstone in 1870, which is the period when the particular clocks to which Mr. Hope-Jones refers were introduced. It is true that Wheatstone did bring out a clock in 1845, but the particular clocks to which Mr. Hope-Jones refers were brought out in 1870. There is a point about the Wheatstone system which is interesting, in that it was the only system in which the hands were kept rotating with a continuous movement and not by impulses. The system answered fairly well, but failed because the wiring was badly done, and the maintaining power was not sufficiently great. It had one great defect in that if by any chance one of the clocks stopped it was not self-starting; it had to be started by hand. The system was one of the prettiest ever invented, but was probably brought out before its time. On page 57, item 4, the author refers to the amount of current which may be used in clocks. I think a great deal too much stress may be placed on current consumption. The cost of current necessary to drive an installation of about 100 clocks may amount to 2s. 6d. per annum, or it may be brought down to 6d. which is one-fifth of 2s. 6d. In either case I hardly think the amount would be worth considering. But it is quite possible that a reduction of that kind may involve a capital expenditure, the interest on which is greater than the amount saved. For instance, an arrangement which costs £10 will represent at 4 per cent. an annual interest charge of 8s.; and therefore, if the annual cost for current consumption is reduced from 2s. 6d. to 6d. at a cost of £10 or at an annual cost of 8s., it is hardly worth while to make the change. Mr. Kempe.

Mr. A. C. Brown: I suggest in regard to the dial that it is quite possible, in fact it has been done, to dispense with the second or locking Mr. Brown.

Mr Brown. click, and with the consequent amount of adjustment that is required when it is used. I have a number of dials running in that way, and the inertia of the hands is ample to prevent the recoiling of the wheel when the driving click is pulled up. A gentle steadying spring friction is applied to the side of the toothed wheel, but with that they run with a current of 75 milliamperes as against the 350 to 400 milliamperes required by the double click dials described this evening, and they have worked for five years without tripping. I will now pass to a much more important subject—the pendulum. My principal object in speaking to-night is to try and induce makers of electrical time systems not to perpetuate that fearful blunder that has been made by good class clock-makers of the mechanical type up to the present. I appeal to them to get rid of the three degree arc, that fearful relic of barbarity. I know the three degree arc is the conventional thing; that is to say, it is considered right to keep the pendulum to a very low, and consequently feeble, arc of oscillation. I know also, of course, that at that arc the circular path which the pendulum describes is, as we are told by mathematicians (who I am afraid have left a large practical part of the subject uninvestigated) more nearly coincident with the cycloidal path which a free pendulum should traverse, and, therefore, that the pendulum may at that amplitude vary its arc more for a given variation of time than it can at the higher amplitude. But notwithstanding that, we know very well in clock-making that a clock keeps better time when it "kicks out well," that is to say, when its pendulum's arc of oscillation is very much more than the conventional three degrees. The fact is the mathematicians have in this as in many other instances only told us half the truth. The investigations on circular error have been based on properties of free pendulums only, with which we are little concerned, because we shall never get one available for clock-timing purposes—even the pulling round of a light counting wheel alters the conditions entirely—but what we are concerned with is how to put power into an oscillating mass to maintain its oscillation against resistances—very small but ever present—and to prevent both the putting in of that power and the overcoming of those resistances (for one is as important as the other) from affecting the time rate of the pendulum or vibrator. For this purpose we want all the circular error we can get, and at most practicable amplitudes could do with a little more of it. Lord Grimthorpe found that a pendulum with an almost perfect cycloidal motion—which can fairly easily be done—caused a good clock to which it was attached to keep very bad time, because an infinitesimal variation either in the driving power or in the resistance to be overcome affects the rate more than the circular error due to the variations of arc at ordinary amplitudes, and is always opposite in sign, so that the circular error at ordinary amplitudes is actually useful in counteracting the escapement errors. The great advantage of a long arc, however, lies in the much greater store of energy then contained in a bob of given weight, and the consequent relative unimportance of given variations in either power or resistance.

Mr. Brown.

It is necessary to take this into consideration, because ordinary clocks, which are competitors to the electrical system, do keep very good time —I am not speaking of American clocks, but ordinary dials such as the one on the wall. There are ordinary clocks with quite ordinary short pendulums hung on without any particular care, having not much weight in their bobs, and being 9 in. in length only instead of the 39 in. or 40 in. of Mr. Hope-Jones's pendulums, and yet with all that roughness they will keep time to within a few seconds a week. Why is that? I believe it is simply because the ordinary clock-makers take advantage of a very good phenomenon of controlled pendulums, and use a long arc, wherein the pendulum is strongly, vigorously, and robustly isochronous, that is to say, it will not be pushed out of its time rate nearly so much for given variations of power or resistance. We go into all kinds of extremes to make the putting in of the power to the pendulum constant, but we cancel a very great deal of the advantage we gain in that way by swinging the pendulum in the short arc where its isochronism is feeble, and wherein it can be put out of time by a very little variation of force. I have been brought up among pendulums for the last thirty years, pendulums made specially for synchronous telegraph signalling among other things, and also for time-work, and have had occasion to find how very little force will suffice to upset the rate of a pendulum, unless that pendulum has a good robust store of energy in itself, and I therefore appeal at the outset to the makers of all electrical systems to abandon the conventions, and to give their pendulums a good long swing. I think they will find by that means they will get a very much greater actual accuracy of time-keeping than they can possibly get by a low swing wherein the isochronism of the pendulum is feeble, and increased accuracy of time-keeping is the principal thing wherein an electrical system stands to gain over the ordinary individual mechanically wound clocks. There are other points in regard to pendulums I should like to touch upon, especially the means of taking out surplus power. It is a fact that with all pendulums, even the Synchronome, we put in a great deal too much power and have to take it out again. Pendulums require very little power indeed simply to keep them swinging, it is the accessories that absorb the energy As showing how very far removed from a free pendulum is even the best of practical pendulums, and the great relative effect of apparently small frictional resistances such as the pulling round by a gathering click of a light counting wheel, it has been calculated that to overcome the aerial resistance alone to the swinging of an ordinary fairly heavy seconds pendulum a single foot-pound of energy would suffice for over a month, whereas the best of driving appliances, such as Mr. Hope-Jones's gravity driver (considering the roller to fall through even a quarter of an inch with a pressure equal to the weight of one ounce every half-minute) puts in something like a foot-pound every seven hours, or about 100 times too much, the difference being expended on the frictional resistance of the counting click and the driving gear, and this with one of the very best of modern arrangements. This shows

Mr. Brown. what a large proportion of the total energy is absorbed by accessories, and how largely little variations in the friction of those accessories, as from varying viscosity of oil and the like, must affect the proportion of power actually given to the pendulum itself. Pendulums, in fact, like men, "want but little here below but want that little long," and we find it impossible to give them that little for a long period without usually supplying a great deal too much. But at the present moment, although we are very careful in putting in the power we usually neglect to take precautions to get rid of the surplus, and we leave the pendulum to get rid of it in the best way it can. The pendulum does get rid of it, principally by varying mechanical friction on the counting wheel, driver, escapement, or other accessories. If it did not, it would soon accumulate its swing and knock out the sides of the case. But the way

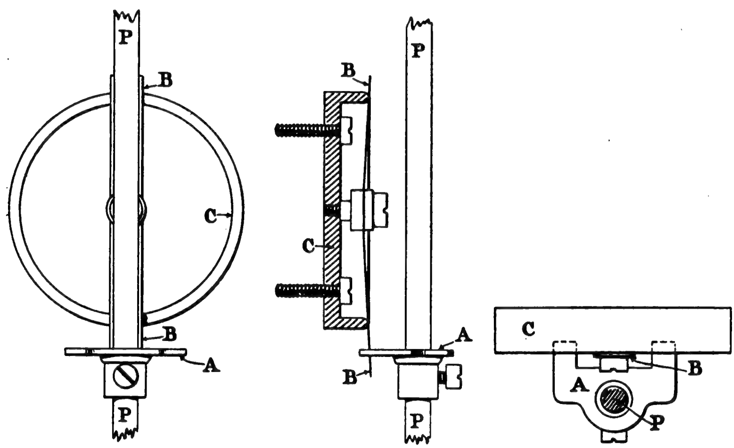

FIG. A. FIG. B. FIG. C.

in which it gets rid of the power is not so well defined as it might be, whereas accuracy in this is just as essential as care in putting the power in. I have devised and have had in use for several years past a method of enabling a pendulum to get rid of this necessary excess of energy in a well-defined way without absorbing any from that required for the proper performance of its work, and without nearly so much as heretofore varying its time rate for any of the small usual changes in course of time of either power or frictional resistance. The arrangement or governor is shown in the sketches, Figs. A, B, and C herewith, which are respectively front and side elevations (partly in section) and plan. Fixed on the pendulum rod P is a slotted plate or fork A, whose notch is just long enough (taken in relation to its height on the pendulum rod, which height is adjustable) to allow the pendulum to make its minimum required swing without touching anything. Beyond this, however, the ends of the slot touch and slightly push round the

end of a light spring B (whose weight is as nearly nothing as may be) which is encompassed by the slot, and which is pivoted near its centre or fixed by a shoulder screw flatwise to a brass-piece C, so that the spring bears with a little pressure near its ends on to a turned ring projection on the piece C, and therefore moves with a little gentle and adjustable spring friction. The result is therefore that the pendulum swings through its normal arc required for the counter quite freely without experiencing any resistance at all from this arrangement, but beyond the exact normal arc the frictional resistance is encountered and the surplus energy soon absorbed. It will be noticed that the spring B does not recoil on or in any way attempt to push back the pendulum rod after having been pushed over, so that the only slight quickening of the pendulum produced by the arrangement is that due to the friction, which can be adjusted in extent so as to quicken the rate for a given super arc moved through exactly to the same extent as the circular error arising from that same super arc slows it, thereby circumscribing the pendulum within close limits and with less variation of time rate than, I believe, by any other means at present known, and certainly much less than by the haphazard methods now in vogue for allowing the exit of the ever present surplus power in any chance variation of amplitude or resistances. It may be noted also that with this arrangement applied it is not nearly so necessary as heretofore to keep the power so constant, because we can absorb a varying excess without varying time, and simpler and more economical methods of driving may therefore be applied. It is also important that pendulums should be hung in a suitable place. In this case the electrical time service has an advantage over the mechanical one, in that the pendulum can be separated from the clock. Pendulums, although they appear strong, healthy bits of apparatus, are much influenced by local surrounding gravitational influences. The best place, therefore, for a pendulum is down in a basement as near Mother Earth as possible. In reference to the oscillograms and the matter of splashy or vibratory contacts, I would point out that a simple method of testing this consists in putting a low resistance telephone receiver into the circuit, or an ordinary receiver shunted. It is then easy to hear any trace of vibratory or "splashy" contacts as scratches instead of sharp clicks in the telephone. If, then, only sharp clicks are heard in the telephone it is quite certain that the contacts are doing well, and that there is no vibration present which will affect any other instrument. Mr. Brown.

Mr. E. T. COOK: The question of keeping the current consumption down, which a previous speaker has dealt with, seems to me to be one which is very much overrated. I think one can easily spend 10s. a year in current, and if one obtains any slight advantages in the way of a better system it is money well spent. While Mr. Hope-Jones has complimented certain inventors on their transmitters, I think he is a little bit severe in his condemnation of some other systems. In one place he says the duration of contact is 100 times longer that is necessary, but taking his lower figure of 0·06 second, and multiplying Mr. Cook.

Mr. Cook. by 100, we obtain 6 seconds, which is quite a long time even for a very badly designed transmitter. I have had some small experience with Mr. Murday's system in connection with an instrument-making class at the East London College. Some of the students worked out a pendulum of this kind, and we adopted it for driving three dials in the Electrical Engineering Department, because of its very great simplicity. We used it in connection with a Foucault-Hipp trip switch, and the result is a very simple and good mechanical job which has operated now for four years with no stoppage due to faulty contacts. I have made some oscillograms of those contacts taken after the system had been operating for 2½ years (Fig. D). If they are examined it will be seen that this form of contact is capable of being made very cleanly and very precisely, the break, though comparatively slow, is

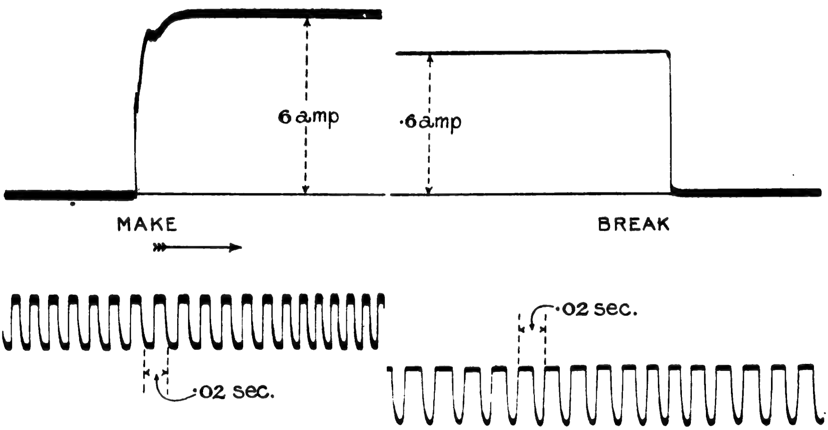

Fig. D.

particularly clean. Three kicks will be noticed at the make, due to the momentarily increased inductance when the dials come on. The pendulum has given to it a very healthy swing so as to make the whole job as mechanical as possible. I should like to ask Mr. Hope-Jones if it would be possible for him to include in his very valuable oscillograms some of a switch which has been operating for a number of years. Most of the oscillograms shown refer to new installations, which will consequently be in the most perfect condition possible. The little kick which is observed in the second oscillogram is due, I believe, to removing a pad which takes up the normal vibration due to the switch arm falling backwards. When that pad gets hard, as it would do in course of time, it seems to be almost possible for that little kick to become something very much greater, and perhaps operate one of the dials and send it in advance of some of the others. I have seen little kicks, which have appeared no larger than that

which have operated dials. Further, some details of actual costs of working a Synchronome switch would be of great value. Mr. Cook.

Dealing with the Murday contact, one can very easily get over the trouble of closing the switch at the end of the swing of the pendulum in this way. A is the 15-tooth wheel and B is the pendulum (Fig. E). If we put a little arm at C and pull the wheel round and have an arm E which closes the contacts D, the arrangement will make contact in the middle of the arc of swing. One point in connection with the design of these contacts is that I have obtained better results by making the length of the two springs different, so that at D there is a sliding of one contact relative to the other. It is interesting to note that whatever work is done in compressing this spring (when one uses the pushing instead of pulling motion) is given back to the pendulum in the return movement, so that its interference with the timekeeping is probably small.

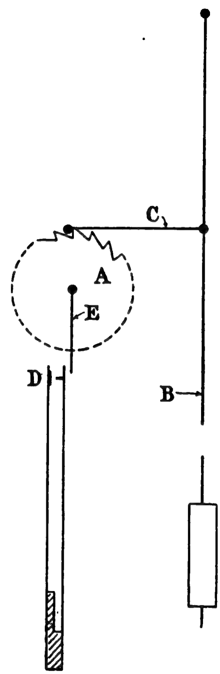

FIG. E.

Mr. J. N. ALTY: Some years ago I had the pleasure of inspecting a number of devices manufactured by Messrs. Lowne and Son, some of which are illustrated in the diagrams, and the ingenuity of the mechanism struck me very much at the time. In comparing the several devices which are described by the author, both in his present paper and in that read by him ten years ago, one is struck by the relative simplicity of the recent form of the Synchronome switch. After some five years' experience of an installation comprising seven dials controlled by a Synchronome switch, it seems that with good wiring and a reliable battery, satisfactory operation can certainly be expected. The oscillograms are very interesting. In No. 13 is shown the rise of the current when 200-volt mains are used, and a 32-c.p. lamp in series. The rise is very sudden, and the author said that the current necessary to operate the dials is therefore larger than in previous cases, owing to the fact that the duration of the period of rise in current is so much smaller. Possibly that might be remedied and the objectionable noise done away with by using an inductive resistance, instead of a lamp, so as to increase the time constant. It would be interesting to know if the author has experimented with dials connected in parallel. There are certain phenomena which arise in regard to the inductive action, which I believe are accountable for many failures of the wiring. These would appear to be partly done away with if the dials are connected in parallel instead of in series as is customary. The wiring would, of course, have to be doubled, but Mr. Alty.

Mr. Alty. one dial failing to operate would not then interfere with the others. Previous speakers have referred to the cost of batteries. The real trouble, I think, with the battery driving of these dials is that when very small amounts of power are taken from a dry battery, in many cases it is found to rot out rather than wear out. That might be remedied if the dials were connected in parallel, because larger quantities of electricity could be used at a time, which might be more economical.

Mr. Duddell. Mr. W. DUDDELL, F.R.S.: I think that the President's opening remarks this evening, in which he referred to Mr. Hope-Jones's absolute fairness in describing other systems, were most appropriate. I do not know whether I am in order, but I should like to suggest that many more diagrams should be inserted in the paper. There are several systems represented on the table which are not illustrated in the paper, and I think it would be a great advantage to the Institution to have illustrations of those systems in the *Journal*, so that this paper may be the most complete record in existence of electric clocks. One of the very first things I ever did in electricity was to try and invent an electric clock. As a boy I remember building an electric clock out of a grandfather's clock, and I had a splashy contact. It would not work. The dial used to go step by step, sometimes six steps at a time instead of one. I got over the difficulty in the end by an elaborate system of chopper switches that went in and out, and did the work properly, but it broke down because I buried cotton-covered wire in the garden, and the wire soon failed. That is a relic of the past. It shows that every one of us who has thought of electric clocks has passed through the stage of splashy contacts, which killed most of these early step-by-step clocks. The independence of the time-keeping element, the pendulum, has been referred to. The pendulum, if it is to keep good time, must not be interfered with by the mechanism more than is absolutely necessary. There is one pendulum on the table which is not described in the paper, that of Professor Féry, of Paris, which is the most ingenious pendulum I have seen. The main pendulum carries a magnet, and works another auxiliary pendulum with a little copper ring on it. At first sight it appears that the main pendulum is absolutely free from any contact, or effect of the contact, disturbing its action. But I believe that is an electrical paradox, because, if the contacts affect the auxiliary pendulum, will they not affect the work required to drive it, and therefore the reaction on the main pendulum? I rather suspect that the contacts might just as well be put on the main pendulum. With regard to the question whether the battery is going to be troublesome or not, this is largely determined by the number of cells in series. If a large number of cells in series be employed to work a large number of dials, I think you will find that the leakage current works out to a much greater number of ampere-hours per annum than the author says is necessary to work the whole of his time system. A very small leakage current will add up in the course of a year to a quite appreciable number of ampere-hours. Ordinary dry cells are not particularly well insulated, for their outside

cases are usually made of zinc, with a cardboard covering. If they stand in a damp passage, or in the basement of a building, the risk of leakage running the battery down is very considerable, especially with a large number of cells in series. With a small number of dials in series there is no trouble from this effect. The next point I wish to refer to is the question of synchronisation. Mr. Kempe, of the Post Office, has suggested that it is less costly to synchronise clocks. I should like to ask if the cost of winding the clocks has been taken into consideration in that connection. It seems to me that the cost of sending a winder round to wind all the clocks, when capitalised, will produce a much larger sum than doing away with the clocks, and replacing them with some of these little simple dial movements. Finally, in connection with the oscillograph curves, I believe that from the little dent in the curves it is possible to calculate the efficiency of the system. When a motor works—and these are really nothing more or less than motors—the efficiency may be reckoned as the ratio between the back E.M.F. and the impressed voltage. The little dent in the curve is caused by the back E.M.F. in the magnet, and it seems to me that the back E.M.F. of the magnet, together with the other data of the circuit, gives a measure of the work actually being done. It would therefore seem that one can actually calculate from these oscillograph curves the efficiency of an electric clock considered as a motor. Mr. Duddell.

Mr. A. E. McCloskey: It is somewhat disquieting to learn from such eminent authorities as Mr. Kempe and Mr. Brown that the action of the master clock—and with it all the other clocks in circuit—can be so easily disturbed, even by some very slight alteration in the stoking arrangements of an ordinary business establishment. It therefore occurs to me to ask whether it is not considered possible to arrange that a current from the Greenwich or other observatory could be used to standardise the master clock and at the same time all the other clocks in its circuit. With the Sychronome Company's clocks such a current might be made to hasten or retard at a particular instant the making of the clock contact; and in systems where an alternating current is employed by a somewhat similar action on a special commutator. Mr. Hope-Jones has explained how in the Synchronome Company's system a bell is rung whenever a battery failure occurs. I understand that on the Continent some device is employed whereby an alarm is given whenever a driven clock is stopped, whether the trouble be due to faulty springs, battery failure, disconnection, short circuit, or earth. I should feel obliged if the author would kindly favour us with some details of the apparatus employed. Mr. McCloskey.

Mr. A. E. Ball: Mr. Hope-Jones in his excellent paper has showed us that it was usual in the early days to employ contacts of comparatively long duration. It is worthy of remark, however, that my first contact arrangement—which was made with a chronometer detent action—was of short duration. After experimenting with several types of master clocks for some years, in 1903, in conjunction with Mr. Hardy Mr. Ball.

Mr. Ball. Parsons, I introduced a novel form of transmitter or master clock, in which the happy combination of the four vital principles were employed, namely: (1) A gravity lever normally supported on a catch; (2) its release at half-minute intervals by the pendulum through a scape-wheel; (3) gravity impulse to pendulum through roller and inclined plane; (4) electromagnetic restoration of gravity lever through contact sufaces. The transmitter was duly patented in 1904, and has been adopted successfully since that date by Messrs. Gent & Co., Ltd., of Leicester. The transmitter is made in a variety of patterns, but all contain the above features, which are also the features of the time transmitter, the advantages of which have been so ably described in the paper. I have to thank the author for including a description of my firm's electrically driven turret movement and its control from an impulse circuit. With reference to the question raised in the paper regarding its suitability for very large clocks, I may say that practical tests which I have made with this movement prove that there is no limit to the size of turret clocks which could be driven by it. Numbers of these movements are in operation in this country and abroad, and are driving turret clocks of various sizes, all with exposed hands. Large clocks with four 10-ft. dials are being driven by a single movement with unqualified success and with a large safety factor of power.

Mr. Hohne. Mr. H. S. HOHNE (*communicated*): It is a curious thing that the gravity lever escapement was occupying so many different independent people's attention during the year 1904, because our movement, although it arrived commercially in 1905, yet was working in our factory for the whole of 1904, and therefore in that respect we are in a line with Messrs Campiche, Palmer, and Lowne, whom Mr. Hope-Jones describes that he followed in adopting the gravity lever escapement. I personally do not agree with Mr. Hope-Jones's subsequent remarks about batteries, because with any form of Leclanché cells, either the wet or dry type, the system taking the lowest current rate in its operation will naturally get the greatest value out of the battery connected to it, because if less current is required from the battery, the internal resistance may rise so much higher, and that is the chief cause of deterioration of any type of Leclanché cell, namely, the increase of internal resistance through several different causes. There is one point about the Magneta system which did not receive much attention, and that is that it does not seem to have been successfully applied to clocks of large diameter, nor the control of turret mechanisms, whereas a battery-driven system is very simple, and can be efficiently applied to the very largest of turret clock mechanisms. In fact, there is now an inquiry on the market for a turret clock as large as (or larger than) "Big Ben," to be operated entirely by electric current. Mr. Hope-Jones describes one type of our transmitter (see illustration Fig. 8), and he says he understands it is now not found to be beneficial. The word "beneficial" in this case might be somewhat misleading. This type was not found beneficial from the com-

mercial point of view only, because we could not manufacture at a price sufficiently low to attract the user of a comparatively small number of clocks, and so we designed our cheaper pattern. I was rather disappointed that Mr. Hope-Jones had not time to get to the end of his lecture and deal with turret clocks. This type of clock is as interesting as any other, and illustrates very clearly the special advantages and the simplicity of electrical operation. Apparently from Mr. Hope-Jones's paper, we are not by any means the first in introducing the particular type of electrically operated turret clock (illustrated in Fig. 11), yet I think we may fairly claim to have done the most to bring this form of electrically operated turret clock to the notice of the public. It is stated in the paper that there may be some limits as to the size of turret clocks to be dealt with by this method, and I have pleasure in stating that the limits of size with this particular form of mechanism are only those of any limits there can be to the actual size of turret clock faces, and this has been actually proved. I think Mr. Hope-Jones's motor controlled by a chaser switch is very ingenious, but personally I do not feel so satisfied as to its effective time-keeping for this reason, that with a very short and heavy pendulum you have a known factor with which to deal, and it is easily dealt with and controlled, but with a motor operated originally at 1,800 revs. per minute geared down to 1 rev. in $5\frac{1}{2}$ minutes, and dependent upon varying high voltage, and the contacts of a chaser switch for its perfect operation, I think it is quite possible for a turret clock to have occasionally a greater time-keeping error than would be considered allowable; but as there was really no formal lecture or discussion on this point, I am open to conviction by practical proof to this undoubtedly clever idea. Mr. Hohne.

Mr. J. W. Black (*communicated*): The master clock shown in Fig. 6 appears to be as nearly perfect as is possible in practice. The dial movement illustrated in Fig. 7 would, however, seem to be capable of considerable improvement. One of the main objections to this type of dial is its noisiness, which renders it quite unsuitable for domestic use. Nervous people find the noise intolerable, and are incapable of reading or otherwise concentrating their thoughts in a room where one of these dials is installed. The silent dial movement recently introduced by Mr. G. B. Bowell seems to meet perfectly the requirements for a domestic clock. I should think that an ideal combination for domestic use would be a Synchronome master clock operating dials fitted with Mr. Bowell's movement. The graphs of the impulses transmitted by the Synchronome switch are most interesting and instructive. No. 1, by the way, shows how uneconomical the master clock is regarded as a motor. The work done by the gravity arm is 9·7 ft.-lbs. per week, whereas the electrical energy used per week is 0·54 watt-hours, which is equal to 1,433 ft.-lbs. The efficiency of the motor therefore works out to about 0·68 per cent. This, however, is of academic interest only, as the power used is so small and costs so little that there would be no great advantage accruing from increased Mr. Black.

Mr. Black. efficiency. The dial movement takes 3·5 watt-hours per annum, which is equivalent to 0·067 watt-hours per week, or 178 ft.-lbs. An ordinary "grandfather" clock takes about 70 or 80 ft.-lbs. per week, and as this energy is necessary to drive a long train of wheel work and escapement, as well as the hands, there would appear to be room for effecting considerable economies in the consumption of electrical energy by the dials. In a small installation of twenty or thirty clocks the energy taken by the dials is at the most a very small affair. It is likely, however, in the near future we shall have standard time "laid on" to our houses in the same way as we have electric and gas supplies laid on. It would, of course, be quite impracticable to wire the whole of the dials in a city in series, and it would be interesting to consider how such an installation might be arranged. Has any attempt yet been made to distribute standard time on a large scale? If so, I think it would be interesting to have particulars of the distribution. Perhaps Mr. Hope-Jones can give us this information. The electrical energy used per annum would not be a costly matter, but it would be an advantage to have dial movements of higher efficiency than at present in order to keep down the cost of the distributing cables.

Mr. Falconar. Mr. O. L. FALCONAR (*communicated*): Mr. Hope-Jones's paper gives one the impression that the author is nothing if not precise, and it behoves him to guard against an error into which many manufacturers of electrical apparatus have fallen, viz., to sacrificing reliability for efficiency. By this I mean the amount of electrical energy required to work a Synchronome time system is apparently so small that he could easily afford to sacrifice a little energy for the purpose of increasing the weight and strength of the moving parts in the controller shown in Fig. 6. This would allow an ordinary mechanic, who has not the delicate touch of a skilled clock-maker, to make any small adjustments required. Another point in reference to all electric impulse systems, which, I consider, is a matter of great importance, is the source of electric supply. The type of battery used has to be chosen with some discretion, as many makes of dry cells cannot be used more than a few months owing to rise in internal resistance. I am personally inclined to favour a small accumulator when a suitable electric supply for recharging could be obtained. Of course, a type of accumulator which retains its charge should be used; and these can now easily be obtained. In regard to recharging, I would ask Mr. Hope-Jones—and I am confident his ingenuity would be equal to the occasion—to design an automatic arrangement worked in conjunction with his time switch, so that the accumulators would get a periodical charge up. These modifications would, I think, make the Synchronome time system as near perfection as it is possible to expect.

Mr. Shortt. Mr. W. H. SHORTT (*communicated*): It is now, I think, generally admitted that the superiority of the Graham escapement, and the magnificent time-keeping obtainable when it is used in conjunction with accurately compensated pendulums, are due to the presence of

Mr. Shortt.

an escapement error which, by suitably adjusting the driving weights of the clock, may be made to compensate for the circular error produced by variations in the arc of vibration of the pendulum. In Sir H. H. Cunynghame's gravity escapement the escapement error has probably been reduced to the smallest possible amount, but in view of the possibility of making use of the escapement error to compensate the circular error, its entire elimination does not seem to be quite what is wanted. It would appear that better results could be expected if, instead of giving the impulse to the pendulum while it is passing the zero position, it were delayed a little. An escapement error would thus be introduced, which would be at its maximum when the arc of vibration, and consequently the circular error, was at its

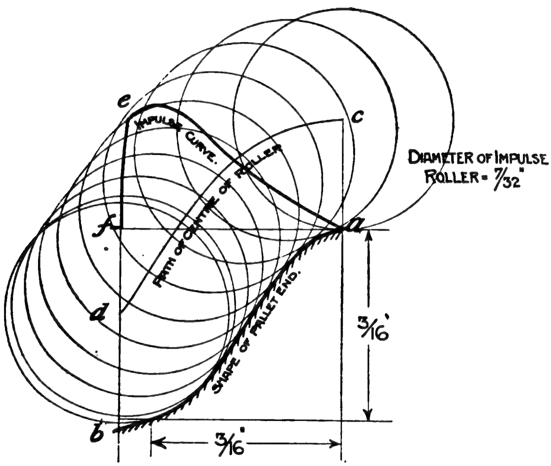

FIG. F.

minimum, and with a certain arc of vibration, to be determined by experiment, the two errors would exactly balance one another. Every type of electrically driven pendulum has its own escapement error, and it is quite possible that in some types it may have a compensatory effect, and the excellent time-keeping obtainable from pendulums which are anything but free, may probably be accounted for in this way.

With regard to the modified Cunynghame escapement adopted by Mr. Hope-Jones, the impulse curve shown in Fig. 9 (page 71) does not appear to be quite ideal, for at the commencement and end of the impulse period the rate of increase and decrease of the horizontal driving force is at its maximum, whereas it should be at its minimum. Also the curve F G represents the path the centre of the roller on the gravity arm should follow, and not the shape of the pallet end

Mr. Shortt. as stated. If the pallet ends are intended to be sine curves they will approximate closely to the curve *a b* shown in the accompanying diagram (Fig. F), and the path followed by the centre of the roller will be represented by the curve *c d*, and the impulse by the curve *a e f*. This last curve clearly shows that the impulse terminates very abruptly even when the roller is allowed to run down to the very bottom of the pallet.

I venture to suggest that a better path for the centre of the roller on the gravity arm is given by the portion of the curve $y = x - \sin x$, from $x = 0$ to $x = 2\pi$, represented to appropriate vertical and horizontal scales by *i k* (Fig. G), for, since the horizontal driving force is directly proportional to $\frac{dy}{dx}$, the impulse curve is represented by the

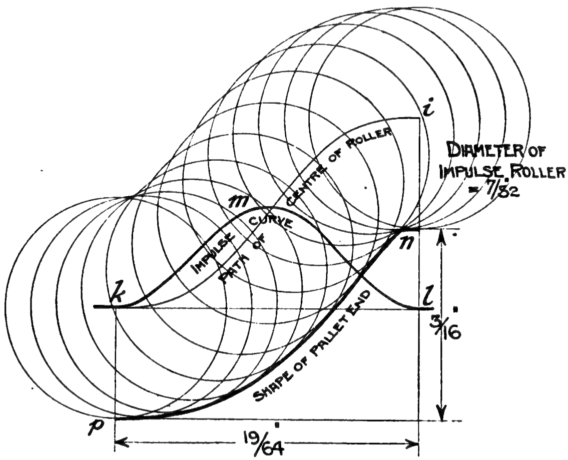

Fig. G.

portion of the curve $y = 1 - \cos x$, from $x = 0$ to $x = 2\pi$ (*l m k* Fig. G). Since the rate of increase and decrease of the horizontal driving force is zero at both the commencement and end of the impulse period as well as at the centre this impulse curve is ideal. The proper shape for the pallet end is given by the curve *n p* (Fig. G), obtained by drawing a number of different positions of the roller, the centre of which follows the curve *i k*.

To obtain the full benefit of a pallet formed as just described the roller must always travel to the extremity of the curved end. An adjustable balance weight would therefore have to be provided on the gravity lever, in order that the strength of the impulse may be varied and the arc of the pendulum adjusted to its correct value.

The President. The President: Before I ask the author to reply, let me take this opportunity of making an appeal, in conjunction with what Mr. Duddell

The President. has just said, to the other makers of electric clocks.* It is very desirable that our *Journal* should contain a full record of the condition of the electrical clock industry at the present moment. We must congratulate Mr. Hope-Jones on the fairness with which he has treated his competitors. Naturally, he could not go to rival makers and say, "Give me all the information you possess," but he overcame the difficulty by referring to Patent Specifications and other printed matter, which are open to all.

Mr. Hope-Jones. Mr. F. HOPE-JONES (*in reply*): In reply to Mr. Kempe, I did not intentionally belittle Ritchie's work; on the other hand, in my opening paragraph I singled out his and one other system as the only survivals of the Victorian era. On the subject of synchronisation, I hope I have not done any injustice to the excellent work which has been carried out by the Post Office engineers in the last year or two. It has been a joy to me to see that the magnificent network of wires possessed by the Telegraphic Department has at last been used for the purpose for which it is peculiarly capable—the actual physical synchronisation of clocks instead of merely sending signals once a day to the various post offices in the country at ten o'clock or one o'clock to assist the clerk to put the clock right by hand. I entirely agree with Mr. Kempe on the subject of non-inductive shunts, and I invariably use them. I am, however, proud of the fact that, thanks to its substantial construction, and the ample power available, the "Synchronome" switch may spark badly and yet continue to work perfectly; nevertheless, to avoid sparking, non-inductive shunts are used. They also have this further advantage. The responsibility devolving upon a really important time circuit of perhaps 100 or 150 dials is great, and being a series circuit the risk of breakdown is mainly the risk of a disconnection. Substantial wiring is put in, say $\frac{8}{20}$ gauge; but the strength of the chain is the strength of its weakest link, and when going through the magnet coils of the dials, thin wire is necessary. It is nice to have a shunt here as an alternative path, as it serves the double duty of absorbing spark and of giving security in a weak place. Mr. Kempe spoke in high praise of Léclanché cells, but we prefer dry cells. The current consumption being so small that no battery has the chance of expending more than 1 or 2 per cent. of the energy it contains during its natural life, I prefer a higher rate of current—up in the neighbourhood of 0·3 or 0·4 ampere. That implies a low-resistance cell. Large dry cells are used on account of their low resistance, their long lasting properties, and the absence of attention required. In order to show that the bogey of battery failure does not amount to much, I submit the records of the clock batteries in half a dozen well-known buildings in London since they were erected (see Table on page 100).

Most of them are ten years old, and the batteries have been replaced twice in that period, the average life being four years. I am sorry if I made a mistake with regard to the date of Wheatstone's

* See Addendum, page 75.

Mr. Hope-Jones.

system. As regards the question of the insufficiency or sufficiency, it was insufficiency I was speaking of most. The great point in any system of electric clocks is to make them, as the Americans say, fool-proof. They have to go to people who do not know how they work and who are sure to make mistakes in erection and management. Neglect is one of the worst enemies that any electrical clockmaker has to face. That neglect will usually result in a system being left without sufficient battery power. The insufficiency will not be enough to stop the master clock—there will still be enough current to keep the system going somehow, usually anyhow, with one dial after another dropping out and the system becoming a laughing stock. I would rather have the circuit stop and strike from work altogether provided it kept its synchronisation up to the last moment the battery was capable of, and

Premises.	First Battery Installed.	Life.	Second Battery Installed.	Life.	Third Battery Installed.
Queen Anne's Bounty ...	Sept., 1900	3 years 10 months	July, 1904	4 years 1 month	Aug., 1908
Surveyors' Institution ...	Dec., 1900	4 years	Dec., 1904	4 years 2 months	Feb., 1909
Institution of Mechanical Engineers ...	On Lighting Circuit		Oct., 1904	4 years	Oct., 1909
L.C.C. School of Marine Engineering ...	Jan., 1905	5 years 1 month	Still Running		
Henry C. Stephens, Aldersgate	March, 1901	3 years 10 months	Jan., 1905	4 years	Jan., 1909
Eyre & Spottiswoode, Dalston	Dec., 1899	3 years 9 months	Aug., 1903	4 years	Aug., 1907

that is what the "Synchronome" system does after giving due warning. I would like to refer later to the question Mr. Brown raised with regard to the 3° arc. There are good reasons why the circular error should not be neglected if the arc is large.

Mr. Cook has had practical and experimental experience of this subject, and I have been most interested in his oscillograms. He seems to have been under the impression that I particularly condemn Mr. Murday's method of making contact off a pendulum, but as a matter of fact, in my paper of ten years ago I illustrated his as the best of all those in which the pendulum charged into springs at the end of its swing. But the best is bad; you should not do the work at the end of the swing of the pendulum at all; you ought to do it in the middle. In his present system the contact is made at the centre—a great improvement, but it is still far from the ideal, because all the energy

Mr. Hope-Jones.

for making contact is derived from the pendulum and its duration is arbitrary. I cannot hope to explain here fully the disturbing effect upon time-keeping, of interference with the freedom of a pendulum at the end of its swing. But one aspect of the question can be simply demonstrated as a result of the harmonic law, that is the time during which the pendulum is subjected to such interference.

In Fig. H, A E is the path of the pendulum as in Fig. 9. The circumference of the semicircle is divided into sixteen equal spaces and verticals are dropped to the base line. The pendulum will pass through these spaces between the verticals in equal times. If a lateral motion of $\frac{3}{16}$ in. is required for making a contact, it will achieve it in a period of $\frac{1}{8}$ of a second if it is at the middle, as indicated by the thick line at C, but if it is done at the end, the pendulum will be engaged on the job for over $\frac{1}{2}$ second. It is mainly at the ends of its swing that the pendulum is measuring time, and the force of gravity should then have perfect freedom to act alone and without interference of any kind. Consider the pendulum bob as being a ball attached to the

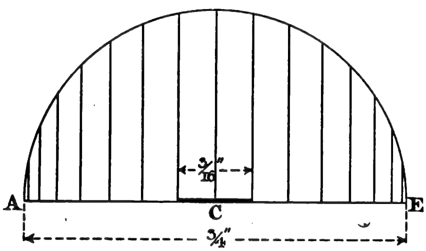

FIG. H.

centre by an elastic string but otherwise free. With whatever force it is thrown out horizontally from the centre it will return to the centre in the same time because *ut vis sic tensio*. Obviously, then, variations of impulse and of friction must be innocuous at the centre and at the centre only. I admit that if the arc of a pendulum could be kept constant and if the springs it charged into were constant, both of which are impossible, the interference would also be constant because the same amount of energy which the pendulum impressed into the springs would be returned to it, the force of gravity would be diminished on the rise as much as it is increased on the fall, and all would be well. But a pendulum driven by the Foucault-Hipp butterfly escapement is the very worst kind to use in this way because its whole principle is that the amplitude of its arc is perpetually varying in irregular frequency which bears no relation to the half-minute function.

In conclusion, it is much better not to give the pendulum any such onerous duty as making contact at all. I have shown how that can be done (with unlimited power from another source) as a result of the

Mr. Hope-Jones.

pendulum merely releasing the gravity lever which is to give it its impulse.

In reply to Mr. Alty, the reason for arranging electrical time circuits in series instead of in parallel is that we want self-induction; and if self-induction exists in the form of an electromagnet in each dial you naturally put them all in series and get their sum. The suggestion of inserting an inductive resistance instead of a carbon filament lamp when driving off a lighting circuit is very pretty, and I am obliged to him for it. Noise does not bother us, because it is easy to make the dials quiet enough for all ordinary purposes. But I freely admit that all rotary forms of dial movements have the charm of noiselessness as a natural result of the rotation of the armature in a magnetic field, whereas a step-by-step dial movement must have a certain amount of noise resulting from its reciprocating action. Nevertheless the new form of dial movement described to-night enables us to provide broad locking surfaces at an angle of 45°, which facilitate soft banking and silent action. With regard to oscillogram No. 13, I would let the action of the dials take place whilst the current is rising, whilst the lamp filament is warming up, so we are better off as regards noise on the lighting circuit than on a battery. It is quite a gentle impulse. The leakage loss of a battery is just one of those apt things that one would expect Mr. Duddell to call attention to, and it enables me, by his mention of it, to illustrate how utterly trivial the consumption of current is. A consumption of something like a watt-hour per annum per cell is nothing compared with the leakage that goes on in a battery of over 20 or 30 volts, even if you put it in a nice dry but cool place. The question of synchronising, raised by Mr. McCloskey, gives me the opportunity of describing to you what has been common practice with us for some years, but which I hesitated to crowd into my paper. In Fig. I the wheel of fifteen teeth (as in Fig. 6) is rotated by the pendulum once every half-minute and has a heart-shaped cam mounted upon it. A lever terminating in a little steel roller is thrust against the cam by an electromagnet precisely at each hour by the Greenwich time signal. What happens is this: Supposing the wheel is late and has not got far enough forward at the end of the hour in its 120th revolution when the impulse comes, the feeler will find the cam in the late position and will throw the wheel forward. Suppose, on the other hand, that the pendulum is gaining and has pulled the wheel too far; when the Greenwich time signal comes at the hour it says, "Come back, you have been going on too quickly." The synchronising magnet pulls the wheel back, with

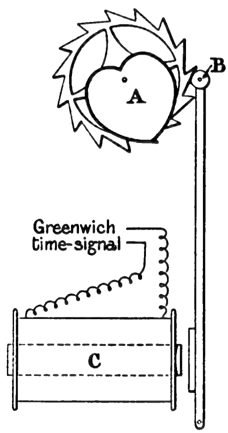

Fig. I.

Mr. Hope-Jones.

the result that that particular half-minute in the whole circuit of dials is shortened by the number of seconds, or rather the very small fraction of a second that the circuit was fast, and *vice versâ*. That is commonly done by us on the hourly service of the Standard Time Company, Ltd., and the daily service of the Post Office. With regard to "reporting back," I may refer Mr. McClosky to my paper of ten years ago.* Herr Puttkamer, of Berlin, was good enough to contribute a full account of the methods of the Normal Zeit Gesellschaft in Berlin, which included a complete automatic system of reporting back any failures in a large circuit of clocks in a municipal time service.

In further reply to Mr. Kempe, as to periodicity, I came to

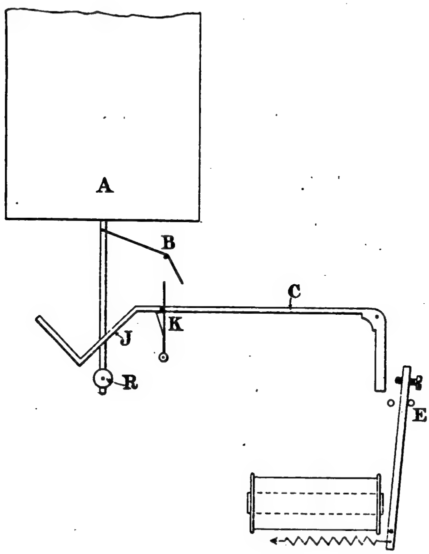

FIG. J.

the conclusion fifteen years ago that half-minute was sufficiently frequent for all ordinary purposes. A national standard is most desirable, and I then deliberately established that standard instead of minute periodicity as commonly adopted on the Continent and in America. In a simple step-by-step dial movement a wheel of 120 teeth is a reasonable limit from the point of view of compact design, simplicity, and economy in manufacture; 240 teeth (which would be required for quarter-minute periodicity) would be more awkward, and gearing is undesirable. Several railway companies have asked me for quarter-minutes, but I have treated it as an unreasonable request, except in tube railways for train spacing, and asked them to accept

* *Journal of the Institution of Electrical Engineers*, vol. 29, p. 286, 1900.

Mr. Hope-Jones.

the standard. Second-by-second progression, the loss of which Mr. Kempe deplores, is useless unless the clock has a seconds hand. You could not read an ordinary clock accurately if you wanted to. On the other hand, an electrical impulse dial gives a definite time-signal every 30 seconds. For observatories and physical laboratories we provide dials indicating every second or every 2 seconds, the impulse being given at every vibration of the pendulum, as in the first application of Sir Henry Cunynghame's escapement to the "Synchronome" switch shown in Fig. J. A count-wheel is dispensed with, and the impulse is given on a little roller R mounted upon the lower extremity of the pendulum, the gravity arm C being released by a chronometer detent escapement B K. The action will be readily understood by comparison with Fig. 6, in which the reference letters are the same.

My statement regarding Wheatstone's system requires but little correction. The acrimonious dispute which appeared in the *Literary Gazette* of June, 1842, shows him to have been the original inventor of the induction idea, and it was this I had in mind in connection with the "Magneta" system. Alexander Bain opened the correspondence with a letter typical of the inventor with a grievance. It was illspelt, and was printed with the editorial note "*verbatim et literatim.*" *Fiat justitia, ruat cœlum!* But I have failed to confirm my correspondent's statement that the set of Wheatstone's clocks, which he bought in 1878, were used in the Houses of Parliament; they were probably those installed in the Royal Institution of Great Britain in 1873 and given up in 1877. The master clock is still in that institution. In further reply to Mr. Brown, the backstop click in a dial movement can only be safely dispensed with when the hands are balanced and are protected by glass from wind and weather. Under such circumstances "a gentle steadying spring friction on the side of the wheel" will suffice, but surely that involves some intelligent adjustment, and I should distrust its constancy. He claims that his dial movements so constructed are more efficient—*i.e.*, will work on less current. I don't see why they should. The figures he gives in milliamperes are no measure of the power required unless either the voltage, the resistance, or the ampere-turns of his magnets are given; and he does not state the duration of the impulse. In my dial movement the backstop J not only gives a positive lock at every point in the cycle of operation, but provides instant facility for disengaging both clicks from the wheel. This is evident from Fig. K, in which 1 shows it in its normal position of rest, 2 part withdrawn, 3 fully withdrawn (end of stroke), and 4 half-way forward in the act of propulsion. The backstop J is never out of the periphery of the wheel A unless the point of the driving click E is between A and H. There is a considerable affinity between Mr. Brown's proposal regarding compensation of circular error and that of Mr. Shortt which follows. Both these contributors recognise the absence in the system I advocate of the escapement error which compensates the circular error in a Graham

dead-beat clock. Mr. Brown proposes to quicken the pendulum on an increasing arc by introducing friction to impede gravity on the upward path, and Mr. Shortt seeks to obtain the same result by displacing the impulse a little out of zero. Unfortunately, Mr. Brown is not correct in saying that variations in power and friction are always of opposite sign to the circular error; if they were the latter suggestion would be quite simple, the pendulum could be quickened by giving the impulse on the downward path before zero, when it would also assist gravity, but the quickening effect would diminish with increasing arc, as I shall Mr. Hope-Jones.

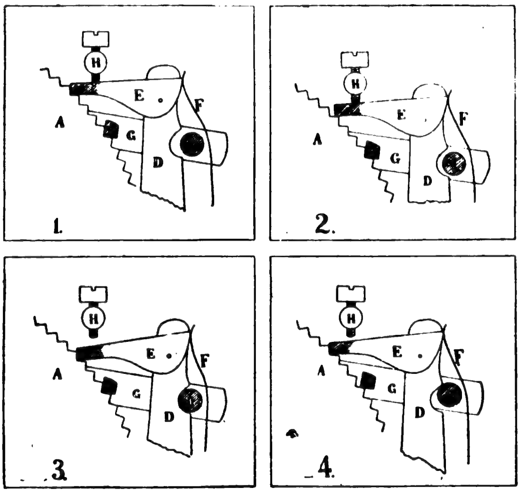

FIG. K.

explain when reviewing it. Mr. Brown's proposal (Figs. A, B, C) is similar in principle to Loseby's isochronal spring shown in the 1851 Exhibition and reported upon by the Astronomer Royal of that time. It was found to be futile when applied to escapement clocks having frictional disturbances of their own, but it might be quite successful here, and I am obliged to him for the suggestion and for his able advocacy of large arcs. His view that some definite means should be found "to get rid of the surplus energy of a pendulum" is certainly a very original way of looking at it, but I cannot endorse the idea. I can conceive of no method less likely to interfere with the isochronism of a pendulum than leaving it alone. The coefficient of friction would have to be determined by experiment in each instrument, and I doubt if any mechanical resistance could be made less variable than air. I have been unable to corroborate Mr. Brown's statement that a single foot-lb. of energy would suffice to keep "an ordinary fairly heavy seconds pendulum swinging for more than a month," assum-

Mr. Hope-Jones. ing ideal efficiency and that nothing but aerial resistance has to be overcome. My experiments and calculations agree with those given by Sir Henry Cunynghame in the *Society of Arts Journal*, vol. lvi., p. 1033, October 30, 1908, and I think Mr. Brown's pendulum must have been a very light one or that such a small amount of energy only sufficed to maintain a very small arc. 25 ft.-lbs. per month is nearer the mark with a seconds pendulum having a bob of 12 lbs. and maintained at an arc of 4°. A comparison with the actual consumption of energy as shown on page 70, 9·7 ft.-lbs. per week (not the larger figures quoted by Mr. Brown, which are arrived at on a wrong basis) shows that the loss by friction is, as one would expect it to be, distinctly less than in the case of a Graham dead-beat escapement and considerably less than with a gravity escapement.

In reply to Mr. Cook, I quite agree that economy of current need not be further pursued. What is wanted is a better adjustment of the load to the battery or the battery to the load. We want a source of current in more convenient form than that of any battery we yet know of. We want one with low internal resistance and ability to achieve its maximum output with a contact time factor of only 0·06 second every half-minute, or 17½ hours per annum. The want of this drove me to experiments with transformers some years ago. I failed in that direction, but I trust some one else may succeed. I have shown that one good dry cell contains enough energy to run thirty clocks for three years, and we want to see it done. Some of my oscillograms show dials working with impulses whose duration is only 0·01, 0·015, and 0·02 second, and I had these in mind when mentioning other systems with contacts whose duration was from fifty to a hundred times too long. The impulses at Liverpool Street station have, or had a few years ago, a duration of 3 seconds. The "Synchronome" switch used in the production of the oscillograms reproduced had been working for twelve months. We habitually neglect the contact and leave it to take care of itself, until at any rate the platinum plate has become badly pitted. Until that stage is reached the oscillograph would show little difference between old and new. Mr. Duddell is quite right, in saying that there is some reaction on the armature bob of Professor Féry's main pendulum as a result of the contact made by the subsidiary pendulum. I had the authority of his Patent Specification in saying that it was subject to two interferences only—air resistance and magnetic check—both of which vary in proportion to the arc so that the isochronism of the pendulum is not disturbed. But he has since informed me that while the disturbance caused by the mechanical rubbing of the contact surfaces communicated to the main pendulum by magnetic reaction is practically negligible, the precise moment at which the contacts begin and finish is not as definite and constant as could be wished, and that might be a source of some slight disturbance. But it is not correct to say that the contacts might just as well be put on the main pendulum. The disturbance is comparatively trivial, and my only regret is that it does not appear to be possible to

make much practical use of this invention because it possesses no powerful switching function capable of operating a circuit of electrical impulse dials. Mr. Hope-Jones.

In reply to Mr. Hohne, the characteristic of the Campiche (1893 and 1899), Palmer (1902), and Lowne (1901 and 1905) systems is the fact that the impulses are given to the pendulum every half-minute instead of every second. They should therefore be referred to as "half-minute impulse escapements," not "gravity lever escapements," of which there are many, but Campiche and Lowne are not among them. I cannot accord the Gent system an earlier place, as their first patent was not published until November, 1905. It contained the switch in an inverted form, but did not mention the impossibility of stopping in closed contact, nor that interesting phenomenon and most useful function, the mechanical assistance rendered by the pendulum to the electro-magnet in the work of replacing the gravity lever, both of which were included in my patent published in July of the same year. With regard to the most suitable current rate, Mr. Hohne is not quite correct in saying that "the system taking the lowest current rate in its operation will naturally get the greatest value out of the battery connected to it"—longevity perhaps, but not greatest value. The essence of the problem is the short contact time-factor. Some thousands of pounds' worth of primary cells driving "Synchronome" time circuits are only devoting to that purpose about 1 per cent. of the current they are capable of yielding during their natural life. He would have us use less; that is why I invert the argument and use the highest current rate which considerations of line and battery resistance will permit. I feel sure that Messrs. Gent's adoption of a pure momentum break similar to that of the "Synchronome" switch, both with and without the insulated screw H (Fig. 5) is due to its merits, and that considerations of expense would not stand in the way of a better device of their own. I entirely agree with Mr. Hohne as to the merits of the "Hipp" system used to drive large turret clocks, and I have always championed it. The model I exhibited but had not time to describe was made by the Standard Time Company, Ltd., and showed their automatic means of introducing an alternative source of electrical energy should the first fail. It also contained their X-suspension spring, which adds strength without imparing flexibility, and prevents wobble.

In reply to Mr. Black, a "pick up one tooth at a time" dial movement can be made inaudible to a sufferer from insomnia—the severest test—by suspending it on springs in its case, and quiet enough to live with by the judicious use of felt, leather, or rubber. Its advantages compared with rotary forms are simplicity, natural dead-beat motion of minute hand, perfect lock, facility for setting by hand or by a zeroizer, and maximum power against minimum pivot friction. Numerous rotary forms are in use such as those in the Grau-Wagner, Peyer Favarger, and Van der Plancke systems, and the type which Mr. Black advocates is in many respects superior, but contains none of the above advantages. They

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are by nature silent and require no special treatment to secure quiet action, but a gear of 1 : 60 must be introduced and the relation of power to pivot friction is necessarily reversed—a serious matter in bad atmospheric conditions. I admit that the efficiency of the "Synchronome" controlling pendulum regarded as a motor is very low, but if Mr. Black had taken wave-form No. 5 instead of No. 1, and allowed for the resistance of the oscillograph it would be just double the figure he gives. The conversion of small and isolated amounts of energy from the mechanical to the electrical form, or *vice versâ*, can never be done efficiently on account of losses in starting and stopping. Rotary dials are no better than reciprocating ones in this respect, unless they are continuously rotating, and in the type he advocates the method of obtaining semi-rotation from single uni-directional impulses, cannot be economical because the electromagnet has to overcome the pull of permanent magnets which are themselves strong enough to move the armature through a considerable arc. The largest area yet covered by any one time circuit in this country is the Children's Infirmary of the Metropolitan Asylums Board, at Carshalton, Surrey. This institution consists of fifty buildings spread over 136 acres. There is an average of three dials in each building, all in series on a single line of about four miles in length (mostly overhead), and operated by one controlling pendulum in the Entrance Hall of the Administrative Building. Equivalent or larger installations would be undertaken in cities if facilities for underground lines were given. A special type of relay embodying all the advantages of the "Synchronome" switch except its time-measuring function would be installed in the basement of each consumer's premises. He would rent this and instal what wiring, battery, and dials he pleased. If he neglected his battery warning or broke his line he would not interfere with the public service. The battery warning in the relay is obtained by a balance wheel instead of by a pendulum.

I agree with Mr. Falconar that, from the practical and commercial point of view, there is much to be said in favour of endowing the pendulum with a superabundance of vitality at the expense of academic accuracy and that the consumption of current is in any case negligible. Even if the proposals for compensating the circular error were impracticable, not one user in a hundred makes observations with sufficient precision to discover it. Storage batteries are quite suitable, and we have many in use. Initial cost and the subsequent attention required are the only drawbacks. We have met the former by introducing a special type of small cell, and if such duties as "topping up" and artificially discharging could be dispensed with, or greatly reduced, we would provide automatic recharging, which, as Mr. Falconar says, is quite a simple matter.

Mr. Shortt's proposal deliberately to introduce an escapement error to compensate the circular error will not be readily understood by those unacquainted with the theory of escapements, and it may therefore be desirable to give some further explanation.

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The circular error is the variation from absolute isochronism due to the pendulum following a circular instead of a cycloidal path; this deviation causes an increase in the time vibration which becomes more and more pronounced as the arc increases. The theoretical values of the retardation in seconds per day due to this for different arcs of vibration are given in the following table:—

Total Arc of Vibration in Degrees.	Retardation in Seconds per Day due to Circular Error.
0	0
1	0·41
2	1·64
3	3·70
4	6·58
5	10·28
6	14·80

If one could be sure that the arc of the pendulum would remain constant the error would be constant, and would be dealt with unconsciously in the act of regulating the pendulum. With a fixed arc of 4° you will have raised your bob and shortened your pendulum by an amount which will make it go 6½ seconds per day quicker than the theoretical length of a seconds pendulum in this latitude, and all would be well. But it is practically impossible to secure a constant arc. It is true that in a "Synchronome" detached gravity escapement the impulse does not vary, for the only thing that could vary is the condition of the oil of the one pair of pivots carrying the gravity arm. But the pendulum has work to do, and although we only operate the count-wheel with jewels running dry, variation in friction undoubtedly occurs, and, to a much less extent, even in the astronomical type (Fig. J) in which the impulse is given at every alternate second near the bob of the pendulum without any count-wheel at all. So we may well look for some means of accelerating the pendulum which shall increase its acceleration proportionately to, and as a result of, increasing arc. And if we cannot find it we can bring the pendulum to time by raising the bob to neutralise circular error at some fixed arc, and look for some means of slowing it in proportion to, and as a result of, its decreasing arc. The rate of the pendulum can be quickened in one of two ways, either by taking energy from it, by causing it to do work, against friction for instance, during its excursion away from zero, or by giving energy to it (*i.e.*, giving it an impulse) during its excursion towards zero, since in either case gravity is being assisted.

The quickening effect of these disturbances is greater the closer the pendulum is to one or other extremity of its swing when they take place. The first of these two methods is adopted to compensate circular error in the Graham dead-beat escapement, because the greater the impulse and the greater the arc (and consequently the greater the slowing rate due to circular error) the greater the friction.

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Can we use the second method—the giving of the impulse to the pendulum during its excursion towards zero—to compensate our circular error? We have seen that its quickening effect will be at its maximum if we give the impulse when the pendulum is just starting upon its excursion towards zero, and at its minimum if we give the impulse when the pendulum is nearly at zero. The position at which we give the impulse is necessarily a fixed one, so if the arc increases, the nearer that point will be to zero, relatively to the total swing of the pendulum, and the less will be the quickening effect. Obviously, therefore, such an escapement error, deliberately introduced to make the pendulum gain, will vary in the same sign as the circular error, and will not only be useless for compensating it, but will make it worse. So we must reverse the process and introduce an escapement error of the opposite kind by delaying the impulse a little so that more of it, or all of it, is given after zero, when it is fighting against gravity, and therefore slowing the pendulum. The slowing rate resulting in a normal arc would, of course, be regulated against in the ordinary way of bringing the pendulum to time by the rating nut.

We cannot make an escapement error which will give us gaining rate increasing with the arc, but we can make a losing error which diminishes with increasing arc and increases with a failing arc, and we permanently shorten the pendulum so that in normal conditions the clock does not lose. Now if the swing of the pendulum increases, that portion of the arc during which the impulse or disturbance of the natural time of vibration takes place, though of the same lateral dimension, becomes less in proportion to the whole, and that diminishes the increase of time which would otherwise be caused. Having regulated the pendulum (raised the bob) to counteract the slowing effect of impulses imparted to the pendulum on the rise, the retardation due to circular error in a larger arc will be counteracted by the diminution of the slowing rate caused by the impulse—a diminution in *time* and in *vice*—in time, because the pendulum travels much quicker at or near the centre when the arc is increased, and in vice, because the impulse is now more concentrated at the centre (relatively to the total swing) where interference is comparatively innocuous.

Conversely, if friction increases and the arc drops, the reduction of the circular error will tend to make the pendulum gain, but the escapement error will increase beyond the amount which the pendulum has been permanently regulated to overcome, and will tend to make it lose.

The amount of artificial escapement error to be introduced and regulated against can, of course, only be determined by careful experiment. The circular error is very small and the investigator must have a clear idea of its relation to barometric error and recollect that mechanical imperfections, want of rigid fixing, and imperfect compensation for temperature, may altogether swamp his observations.

It should be noted that the escapement error Mr. Shortt proposes will only operate during a small part of one-quarter of each complete vibration of the pendulum. Mr. Brown's appeal for a large arc has led

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me to give this proposal considerable space. But for that I should simply have expressed my personal preference for impulses imparted at zero combined with a small arc in which the circular error is negligible. I admit the advantages of a large arc in a commercial article, and I would prefer this method of dealing with the inevitable circular error to the introduction of frictional devices. I am greatly indebted to Mr. Shortt for working out the proper shape of the impulse pallet: his Figs. F and G are quite correct. The Aron Meter Company say that "the ordinary clock" as a method of measuring time (presumably a Graham dead-beat escapement) cannot be beaten, and ought not to be departed from, thanks to the many hundreds of years

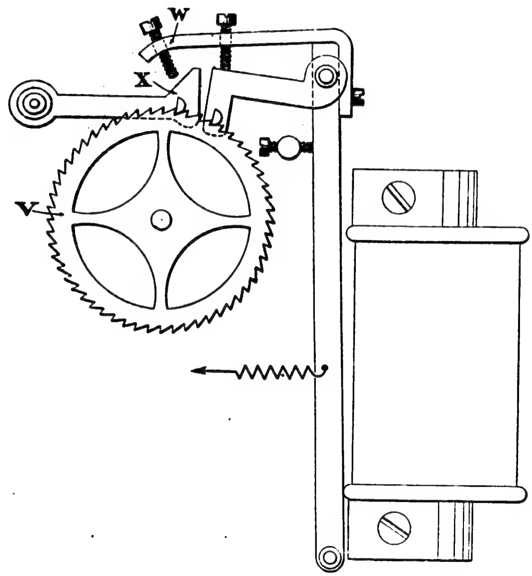

Fig. L.

devoted to its perfection. In all I wrote about the Cunynghame escapement in the form of a "Synchronome" switch on its introduction three years ago, I hesitated to claim superior time-keeping, but experience enables me to do so now; there was never any question as to its safe-going and freedom from the ills that clocks are heirs to. I selected Fig. 8 to illustrate Gent's system from a later patent assuming they would prefer to have it represented by a pendulum more or less free except at zero. That shown in Fig. 14 is engaged in doing work at the end of its swing, and the disturbance caused by the release of the gravity lever and its resting upon the pallet will vary with varying arcs in that part of the path of the pendulum where such disturbances

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will have their greatest effect. There has been no lack of experience of the locked dial movement which Messrs. Gents describe in Fig. 16. The best known form of it was introduced by Victor Reclûs, of Paris, in 1895, as illustrated in Fig. L, and has been very extensively used abroad. I did not adopt it because the whole shock of the momentum of heavy hands is taken on pivots instead of on a substantial stud or projection on the plate. There is nothing in the nature of a vice-like grip if the driving click is made slightly wedge-shaped; and the earlier form provides no facilities for disengaging the clicks from the teeth of the wheel.

Messrs. Gents' proposed method of synchronising in the "B.P." system (Fig. 17) appears to me to hide an underlying fallacy. It cannot synchronise at all, but will only "rock" the error backwards and forwards, fast and slow. The wave-lengths of the oscillations are, of course, dependent upon the amount of correction effected by the synchroniser at each hour, but the amplitude of the waves will

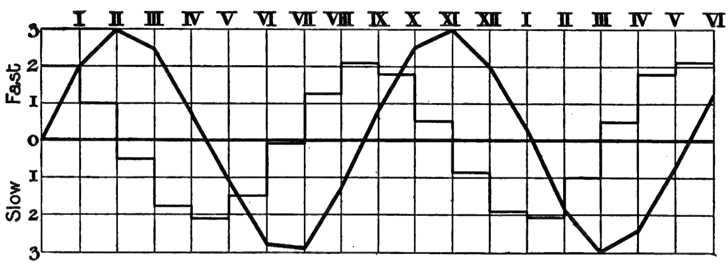

FIG. M.

never diminish. The mistake is due to the confusion of two quite different things, the rate of the clock and its indicated error, *i.e.*, the divergence of the hand from true time. The "B.P." system attempts to synchronise from the latter by repeated alterations of the rate proportionate to the extent of the error; but these alterations are cumulative, and an error of equal value is piled up in the opposite sign. In Fig. M the initial error is taken as being + 2 per hour (whether seconds or minutes is of no consequence), and it is assumed that an error in the pointer of that angular dimension will enable the synchronising feeler to lower the weight on the pendulum one-half of the amount necessary to correct that error. The rate appears in steps as altered hour by hour by the synchronising signal. The thicker line shows the divergence of the hand from true time, or, in other words, the indicated error.

If R is the rate and K the correction constant, then approximately $\frac{R}{\sqrt{K}}$ = amplitude of the vibration and $\frac{2\pi}{\sqrt{K}}$ = period of vibration. Thus in the above curve the amplitude is 2·828 and the period 8·9

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hours, and if we make $K = \frac{1}{4}$, the amplitude is 4·0 and the period is 12·56 hours. If the correction is exact ($K = 1$) the amplitude is 2 and the period 6·28 hours. If, therefore, the synchronising line broke down, the interruption would be just as likely to occur when the rate was at its maximum minus or plus, as when near zero. A "false" or "rocking" synchroniser of this class might have a small field of utility if rigorously confined to seconds and used to oscillate a very small error, if it were not for the fact that it is quite easy to make a true one in other ways. In fact, it was done by Rudd of Croydon, in 1898, and the large bracket clock of Messrs. Thomas Wallis & Co., in Holborn, has been successfully synchronised by his apparatus since it was erected in 1905.

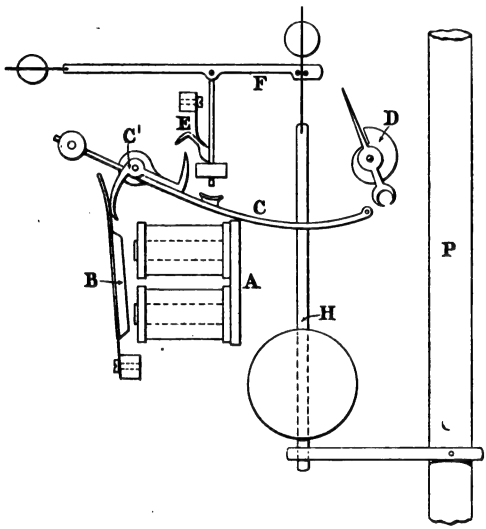

FIG. N.

In Fig. N, A is the synchronising magnet operating the armature B which raises the feeler C through the medium of the **Z**-shaped lever C_1, which latter releases the clutch E and allows the slide F on the pendulum suspension spring to fall and to be re-set into whatever position may be dictated by the cam D. The short pendulum H is a subsidiary one linked to the main pendulum, and is the exact equivalent of the collar weight H in Fig. 17. Now, although Rudd's cam D moves with the clock, as does the pointer D in Fig. 17, and therefore indicates the error of the clock, it is important to note that the synchronising action is not cumulative, and that the rate of the clock is altered afresh at each hour in accord, not with the divergence of the clock from true time, but with the error in its rate. That makes all the difference, and if the correction constant is exact ($K = 1$).

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Rudd will correct the rate at the first operation and will leave it correct, subsequent synchronising impulses having no effect. If K is less than 1 the rate will be corrected by a few successive signals, and left correct. If K is between 1 and 2, the rate will be brought to zero by a series of oscillations, which will take longer and longer to die out as K is nearer 2. But the correction constant must not amount to double the rate. If it does, it will oscillate to the full amount of the error, and if K were to exceed 2 the oscillations would increase in amplitude until they became infinite. It will be observed that only when the pendulum is of the original and proper length will the hands

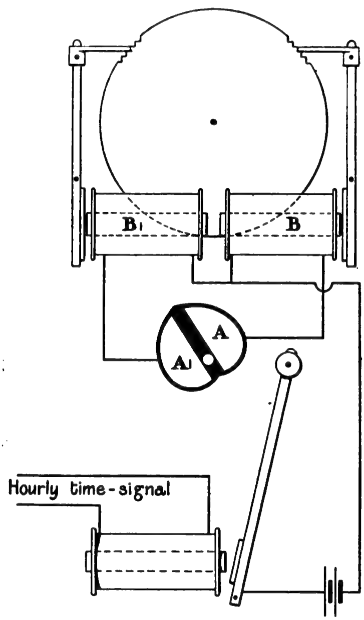

FIG. O.

show correct time. Whenever there is any adjustment to be done as a result of rate the hourly impulse will correct the pendulum, but will leave the hands permanently fast or slow to the extent of the largest last corrected error. The cam will take up whatever position is necessary to secure the right length of the pendulum, and as both it and the clock hands are fixed to the wheelwork the latter should be set to zero when the rate has settled down. The ideal synchroniser is one which both corrects the rate and sets the hands. There is no difficulty in this, and I have devised several ways of doing it. It simplifies the problem greatly, because if you zeroize the hands at each hour, the indicated error becomes the rate. Take, for instance,

the cam A of Fig. I and divide it into two insulated halves, as shown in Fig. O, as a commutator with two segments—A, A_1—connected respectively with a raising or accelerating magnet B, and a lowering or slowing magnet B_1. The synchronising lever is a conductor from battery, and if it habitually finds the cam slow it will operate the raising magnet which will wind up the capstan by means of an ordinary electric impulse dial movement, whereas if it finds the cam fast it will lower it. There is little use in making the correction proportionate to the error; it will soon find zero and keep it. Give it a small correction constant and let it work off the rate at its leisure. Mr. Hope-Jones.

The PRESIDENT: I now ask you to accord a hearty vote of thanks to Mr. Hope-Jones for his valuable paper. The President.

The meeting adjourned at 10 p.m.

BALANCERS FOR THREE-WIRE SYSTEMS.

By A. G. COOPER, Associate Member.

(*Paper received from the* MANCHESTER LOCAL SECTION, *January* 20, *and read at Manchester on February* 8, 1910.)

The author having been asked by some of his brother engineers as to the performance of a static balancer which he installed a couple of years ago, thought that some information on this point might be useful, so he considered to write this paper not only to cover static balancers, but to try to embrace the whole field of balancing, giving his own experience with some machines, and also to collect other useful information and still further to elicit particulars which he hopes will be forthcoming during the discussion.

During the past two or three years articles have appeared in the Press on this subject, notably one by Dr. Garrard on "The Theory of Static Balancers," but the author is unaware of any comprehensive paper on the subject being read before this Institution.

The aim of every engineer is, of course, to balance his system, if possible, by judicious connecting up of his consumers, but it is impossible to do so for all hours of the day and days of the week, so he wants the most reliable and at the same time economical piece of apparatus to do the necessary when called upon. Frequent causes of out-of-balance current are arc lamps for cinematograph entertainments, but the author has declined to supply these except through motor-generators, as he found it was imperative to adopt this course on his small network. He is pleased to say that he has a very small out-of-balance current, and it has therefore been necessary artificially to produce the out-of-balance tests given later in the paper.

There are several forms of continuous-current balancers, but the one most commonly used consists of two shunt machines mechanically coupled together, with their shunts cross-connected, viz., the field being connected to the opposite side of the system to that of the armature which is rotating in it, as shown in Fig. 1. The two machines must be of such capacity that they are capable of continuously carrying a little more than half the observed out-of-balance current. It will be seen from Fig. 2 that the current flowing in the middle wire splits itself, part going through M and part through D. There will be more current through M than D, which in the diagram represents motor and dynamo respectively when the out-of-balance current is flowing in the direction indicated. The action of the machine depends upon an increase or decrease in voltage on either side of the system. If there

is an out-of-balance current on the negative side the voltage on that side will fall in proportion to it. This will produce a weaker field at A in which No. 2 armature is running. It now acts as a motor and increases in speed and drives No. 1 faster. The increased speed will naturally produce a higher voltage, which is still further increased by the field in which No. 1 is running, as it is connected to the positive side. The negative voltage will thus rise, but being the heavier side will still be

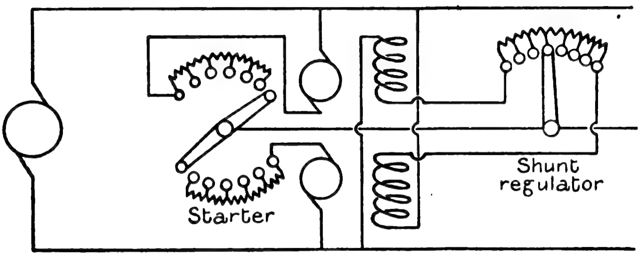

FIG. 1.

lower than the positive. The extent will be according to the design of the balancer. The machines act as dynamo or motor according to which side is out of balance.

The following figures give the tests of a machine of this type capable of dealing with 150 amperes out-of-balance, at the same time driving two boosters 80 volts 80 amperes each on a 480–520-volt system. The machine was disconnected from the middle wire and

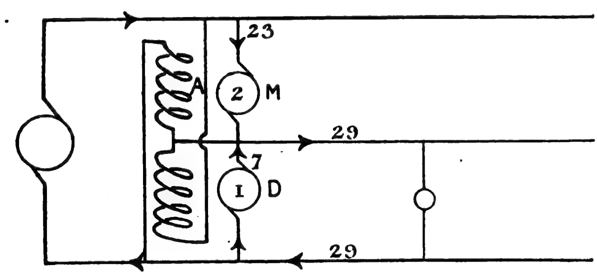

FIG. 2.

driven as a motor and was found to take 8·3 amperes at 500 volts, viz., 4·15 units. The fields took 1·3 amperes, which are included in the consumption given. The boosters were not excited, but the armatures were mechanically coupled, so there would be the loss due to friction and windage.

The voltage varied to the extent of 1 volt for every 10 amperes out-of-balance. This works out at 3 per cent. difference at full load.

Fig. 1 illustrates a good method of starter, and also a centre contact field regulator to enable the attendant to alter the voltage due to the out-of-balance current so as to maintain the voltage equal or, if necessary, raise it on the out-of-balance side; but this is not necessary unless it is desired to take charge of only a single feeder, because if it is running on the station busbars the voltage on one side to suit one

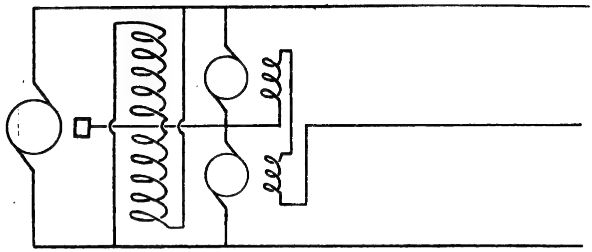

Fig. 3.

feeder would probably act detrimentally upon the other feeders, unless they were all out-of-balance on the same polarity.

An improvement on the above figure, viz., 3 per cent., can be obtained by putting on some series turns to compensate for the armature drop, but to get the best effect and to avoid other complications in case of a heavy short these coils should also be cross-connected (see Fig. 3). The action of the series winding will be as follows: The motoring current, which will be the heavier, will pass round the

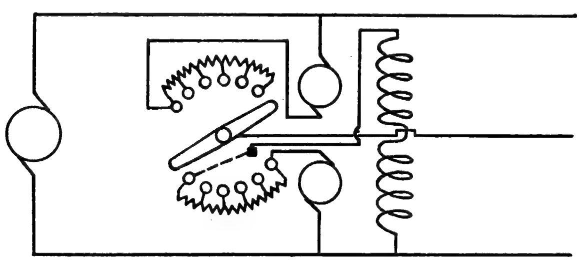

Fig. 4.

dynamo fields in the same direction as the shunt current, thus producing a strong field. The dynamo current will also flow round the motoring side field, but in opposition to the shunt, which will have the effect of speeding up the armatures, thereby raising the voltage on the out-of-balance side. By over compensating the armature drop by additional series turns the out-of-balance side can be even raised above the opposite side.

In Fig. 4 another form of balancer is shown. This machine has a

single shunt field connected across one of the outers and the middle. It has a double-wound armature with a commutator at each end. This is rather a poor balancer and is really only a middle wire former. It is rated to deal with 25 amperes out-of-balance, but is only used for very light loads and during the early hours of the morning instead of running the larger balancer, as the author has no battery in his works. This machine was very much improved by using a more suitable type

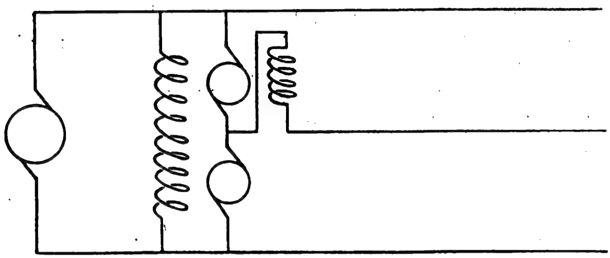

FIG. 5.

of brush than was supplied with it. The power absorbed to drive this machine is 1·125 k.w. per hour.

In Fig. 5 a balancer of somewhat similar construction is shown, inasmuch as it has a double-wound armature with a commutator at each end, but the armature is specially wound, one set of windings being shorter than the other, as shown in Fig. 6. This does not show

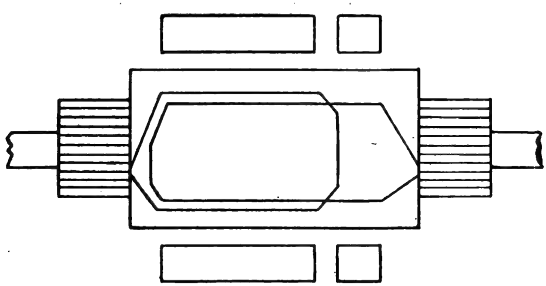

FIG. 6.

the true positions of the conductors, as it is a 2-pole machine, the conductors being drawn thus for clearness.

As the end-windings of the left-hand side are placed between the main and auxiliary magnets, the conductors from that end do not come under the influence of the auxiliary magnet. The main magnet is shunt wound and connected across the outers. The auxiliary pole has a series winding only, which is connected in the middle wire. It will thus be seen that the polarity will change according to which side is out-of-

balance, and the pole strength will vary according to the extent of the out-of-balance current.

The short lengths of the windings of the right-hand side will have voltage induced in them either in conjunction or in opposition to the remainder of the windings rotating in the main field. This type of machine has been in use for a number of years at Blackburn, and has given every satisfaction. It will maintain the voltage equal within 1 per cent. over the whole of its range. This type of machine, of which a sketch is given in Fig. 7, can be wound, I should think, to give a perfect balance or even to boost the out-of-balance side unless troubles are experienced with the magnetisation due to the weak currents when there is a small out-of-balance, or to the residual magnetism when the balance is perfect. This could be got over by having a shunt winding

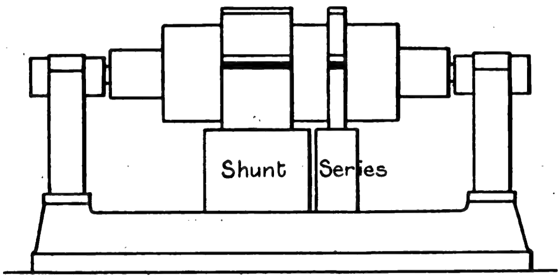

FIG. 7.

and so work on a flatter point of the magnetisation curve and let the series winding help or oppose it according to its direction.

The latest form of continuous-current balancer is known as the C.M.B. (see Fig. 8). This machine has only one armature, one commutator, and one set of brush-gear. This type has several advantages over other types of continuous-current balancers, such as high efficiency, combined with close regulation, small weight, and floor space occupied, little wear and tear as the machine is run on ball-bearings. It will be noticed that the armature which is ring-wound is divided into two equal parts by the short-circuited brushes; the polar limbs are all equal in dimensions. The series compounding coils are arranged on all the poles, not only for the purpose of regulation of voltage, but also to balance the circulating current across the short-circuited brushes. It will also be noticed that the shunt coils are cross-connected.

These efficiencies of these machines are 4 or 5 per cent. higher than can be obtained with two machines coupled together, and the price at the same time is lower.

I do not think it necessary to give further particulars of this machine, as it was described in the technical Press only last summer, and has been reprinted in pamphlet form and largely distributed by the makers.

STATIC BALANCERS.

The use of static balancers or equalisers in this country has mostly been used in connection with rotary and motor-converter installations as it lends itself very readily to this class of work by making use of the secondary coils of the transformer, by connecting the middle wire of the system to the star-point of the secondary coils of the transformers which are supplying the rotaries. In the article referred to at the commencement of this paper, this is shown to be bad from an efficiency point of view, and it is also shown to be better to use a separate static balancer than to use the secondary coils.

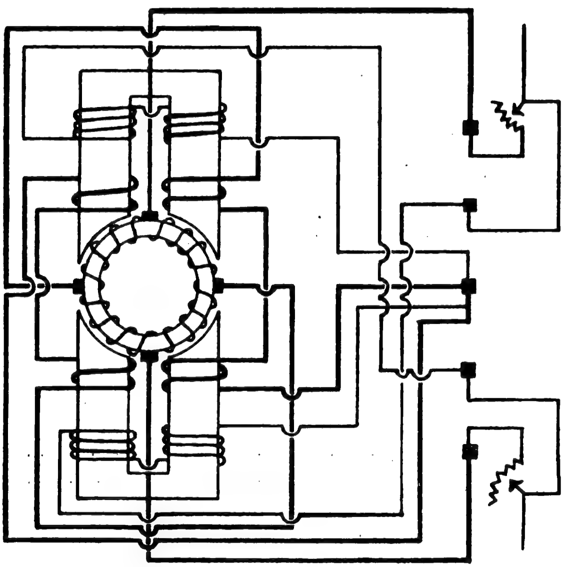

FIG. 8.

The static balancer consists of a choking coil or a transformer core, wound with only one winding on each limb according to the number of phases used. The terminals are connected to equally spaced connections round the armature of the dynamo to give the selected phase proposed to be used. From the slip-rings an alternating E.M.F. is obtained which is connected to the terminals of the choking coil shown in Fig. 9 as a 4-pole for clearness, which in this case is a 3-phase balancer; the star-point is connected to the middle wire. When the system is balanced, there will be a strong choking action which will prevent any large flow of alternating current from the slip-rings. When an out-of-balance current flows through the balancer and the armature there will be a drop in volts due to the resistance,

but this will be shown later to be practically no greater than in most balancers, if the static balancer is suitably designed.

The advantage of a static balancer, compared with an ordinary balancer, is that in the former case there are only brushes running on slip-rings, as compared with brushes on commutators, armatures, field coils, bearings, and starter, and also greater space required. They are high in efficiency and automatic in action.

I find that some makers prefer single-phase, others 2- and 3-phase, but Dr. Garrard has shown that the greater the number of phases used, the better for regulation. For single-phase he gives a difference of voltage worked out on an assumed internal drop in the armature on a 10 per cent. out-of-balance as 0·66 per cent., 3-phase 0·58 per cent., and 6-phase 0·49 per cent., but I hardly think from a commercial point of view that it would be advisable to have more than three phases, unless the slip-rings are brought outside the bearings, as the increased length of the armature shaft will necessitate a larger diameter and a larger bearing, which in a big machine would run up the expense, besides being undesirable from a mechanical point of view.

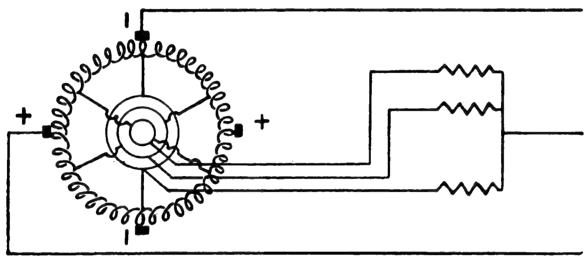

FIG. 9.

The author has installed a 360-k.w. 8-pole dynamo 520 volts, 700 amperes, 350 revs., fitted with slip-rings which are large enough to use the machine at full load as a 3-phase alternator if required. The static balancer is designed to deal with an out-of-balance load of 170 amperes. The machine has a compound winding for traction purpose only, so it is run as a shunt machine when using the static balancer. It might be as well to mention here, that in the event of using a static balancer with a compound wound, or a machine with commutating poles, the series winding must be split, half being connected in the negative side and half in the positive side of a generator, otherwise the static balances will not give the true middle—viz., the volts will not be equal between the middle wire and each of the outers, due to the lost volts in the series winding.

Of course, this will not be noticed at no load, but the difference will be greater as the load increases.

To take an example, assuming that at full load the resistance of the

series turns causes a loss of 1 per cent. of the armature volts in a 500-volt machine, the neutral and one of the outers would be 5 volts higher than the neutral and the other side in which the series turns were connected.

The following tests were taken on the static balancer :—

Out-of-Balance.	+ Volts.	− Volts.	Difference.	Per Cent.	Per Cent. Full Load of Balancer.	Per Cent. Full Load of Dynamo.
Amperes.			Volts.		Per Cent.	Per Cent.
10	257·0	258·0	1·0	0·2	6	—
43	257·0	258·5	1·5	0·3	25	6·1
60	257·0	259·0	2·0	0·4	35	8·5
80	256·5	259·0	2·5	0·5	47	11·4

From the foregoing tests it is reasonable to assume that the difference in the voltage across the middle and the outers would not exceed 1 per cent. at the full load of the static balancer. The static balancer in the case mentioned has one-quarter of the capacity of the generator. If very heavy out-of-balance currents have to be dealt with, in proportion to the size of the static balancer and generator, then a middle wire booster can be attached to the machine to boost the out-

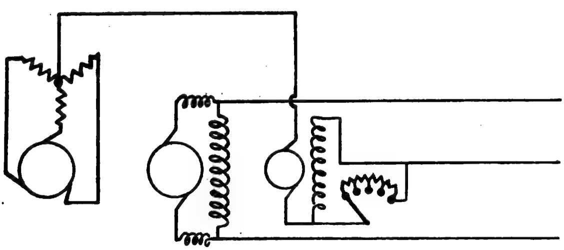

FIG. 10.

of-balance side (see Fig. 10, which illustrates a rotary converter installation on the low-tension side). To vary the voltage, if required, a diverter resistance is fitted across the field which is series wound and connected in the middle wire.

In conclusion, I wish to express my indebtedness to those who have given me information on this subject, and to the members of my staff who have assisted me in the preparation of this paper, and to apologise to my fellow section members for the brevity and shortcomings of the paper, but hope it may promote a good discussion.

Discussion.

Mr. Peck.

Mr. J. S. Peck: I do not quite understand the arrangement of the machine with the two 80-volt 80-ampere boosters described on page 117, and would be glad if the author would make it a little clearer. In the same paragraph loss per kilowatt per hour is given. It should be kilowatt-hours per hour, or units per hour, or simply kilowatt. It is also stated that "the voltage varied to the extent of 1 volt for every 10 amperes out of balance." Does that mean there was a drop of 1 volt on that side, or the difference between the two sides was 1 volt? That is a point that has to be given some consideration in specifying regulation of balancers, because if the voltage across the outers remains constant, and the voltage on the loaded side drops 1 volt, the other side will rise 1 volt, and there will be a difference of 2 volts between the two sides. On page 121 it is stated, with reference to 3-wire rotary converters: "This arrangement is shown to be bad from an efficiency point of view, and it is also shown to be better to use a separate static balancer than to use the secondary coils." I do not see why the arrangement in which the middle direct-current wire is connected to the neutral of the transformer should be inefficient, as the secondary coils have a far greater cross-section than can be used ordinarily in a separate static balancer, while if the coils are properly arranged there is no magnetic effect from the direct current. If, however, the rotary converter is a 3-phase machine and the ordinary arrangement of 3-phase transformers is used, the direct current produces a strong magnetising effect on the core, and the magnetising current of the transformers is increased greatly, and there is also an increase in the losses of the transformer. To avoid this difficulty the "interconnected star" system is used on the secondaries of the transformers. This system is shown in Fig. A. The secondary winding of each transformer is divided into two parts, the phases being cross-connected as shown. When direct current flows in at the neutral point it divides and flows in opposite directions through each winding, so that there is no resulting magnetisation from these currents. A similar arrangement should be used when a 3-phase static balancer is used with a direct-current generator. In designing static balancers for direct-current generators it must be remembered that the frequency is usually very low, and the induction in the magnetic circuit of the balancer must be kept much lower than the heating in the iron demands, for if the balancer takes a heavy magnetising current there is apt to be a flicker on lamps connected to the circuit. This is particularly liable

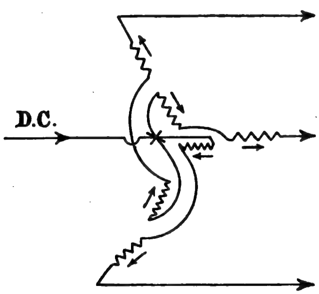

Fig. A.

to occur with single-phase balancers. Two- and 3-phase balancers are used to avoid this difficulty, and also to give a more uniform distribution of current in the armature. Mr. Peck.

Mr. H. GRAY: The first part of the author's paper is now pretty well standard practice, but I notice that in nearly all the illustrations of the ordinary type of balancer the fields are shown crossed. This tends, of course, automatically to equalise the pressure on the two sides of the middle wire. If it is in a place under close supervision there is no objection to this, but if a machine of this class is in a sub-station or other isolated position, and a heavy overload or short circuit comes on the distributors, serious damage is likely to occur to the machine. It may either run away through excessive weakening of the motor field, or flash over owing to extreme overload. This risk will be much intensified if crossed series windings are used. On page 123, with regard to the table giving the maximum out-of-balance (in the first column) at 80 amperes, I see that the maximum out-of-balance the machine was designed for is more than twice this, viz., 170 amperes. Apparently there was no load on the outers of the generator unless there was a constant load on all tests. Of course both the amount of out-of-balance current going from the static balancer and the general output of the generator will make a difference to the equality of balance on the middle wire. We have at Accrington a 200-k.w. motor dynamo, the motor side generally running off traction generators and the generator side supplying general supply. A static balancer is arranged to work off this latter side. I took a few figures the other day on this machine. The load on the outers of the generator side was varied from ¼ load to full load, and the current out-of-balance taken from the static balancer from zero to 100 amperes. With ¾ load (300 amperes) on the outers and 100 amperes taken from the static balancer (which totals to about full load on the plant) the percentage variation on either side of the middle wire from the normal was 2·4 per cent. This amount of variation is probably quite good enough for commercial working in the majority of circumstances. As regards the utility of a static balancing machine, in my mind a machine of this class is very much more useful than the ordinary balancer, and in the case of a short circuit affecting the middle wire it will stand up to the shock much better than a rotary balancer built for the same work. If a static balancer is right on the distributors for all ordinary classes of work, it will be probably found quite satisfactory for commercial balancing. If a feeder intervenes between a distributor and the static balancer, it may be necessary during the hours of darkness to have a middle wire booster in addition; but even in this latter case, during daylight working, no middle wire booster will be necessary. Mr. Gray.

Mr. G. W. WORRALL: On page 119 Mr. Cooper refers to the improvement which he effected by changing the brush. If he can give any more information I should like to have it, as from my own experience the brush is a very important factor, more than the ordinary engineer realises. The author, first of all, says that it is not a satisfactory method "to connect Mr. Worrall.

Mr. Worrall.

the middle wire to the star-point of the secondary coils of the transformers which are supplying the rotaries," and then he proceeds to advocate the use of a static balancer. In the La Cour motor converter, in which there is an induction motor on the same shaft as the rotary converter, the induction motor acts partly as a mechanical driver for the rotary converter and partly as a transformer; that is to say, the rotor of the induction motor runs at half its synchronous speed, and the middle wire is connected to the neutral point of the rotor of the induction motor. Now this arrangement appears to possess the disadvantage of the transformer, and at the same time the advantage of the static balancer. In this type of machine the full advantage of the static balancer can be obtained, because the connecting wires from the rotor to the armature converter can be any number desired, there being no slip-ring connections. Another method of balancing sometimes employed is to change over the station auxiliary plant from one side to another. I have seen this done with considerable success where the out-of-balance fluctuations are not very great.

Mr. Atchison.

Mr. C. C. Atchison: The paper deals with a subject of interest to central station engineers and manufacturers. It is a very essential point for supply undertakings to be able to deal with their out-of-balance, and I am sure the particulars given will be of use to us all. No doubt central station engineers will have seen different types of balancers in the different stations they have been in, and I think Mr. Cooper has collected the main types together for us. Mr. Worrall has referred to the use of the auxiliary plant for purposes of balancing. That is all right, in the earlier stages, as far as my experience goes, but there is little doubt that the auxiliary plant later on becomes a very small proportion of the load, and the amount of switching over would almost make the arrangement impossible. I may say I did it originally, but when later I had to make certain other alterations, I pulled out the change-over gear and arranged for the station and auxiliary plant to balance as far as possible. In connection with the balancer booster, I do not know whether I have misread Mr. Cooper. He speaks of a booster set on page 117, which I take to be a booster for battery charging purposes. Mr. Cooper has spoken of having to deal with sudden out-of-balance. One does get on a supply system out-of-balances at certain times of the week which change slowly and regularly from time to time, but also out-of-balances which one cannot reckon to deal with because they come on suddenly, and are off again very rapidly. I am very glad Mr. Cooper has been able to deal with the question of cinematographs, as these loads are very trying for a small undertaking, but when the consumer finds he only wants, say 60 to 80 volts, and has to pay for units consumed based on a voltage of three or more times that pressure, he will probably wish to effect some saving, as by use of a motor-generator, and so the trouble will sooner or later right itself. In Rochdale we have three permanent cinematograph entertainments, and about two occasional ones; then the theatre requires much more light some weeks than others. When these occur, a balancer which will

rapidly deal with the extra demand and maintain a steady voltage, is absolutely essential. Mention has been made of La Cour converters. I have heard that they were satisfactory at Manchester, but I would not like to put it on record as being correct. I put some in three or four years ago, hoping to utilise them for 3-wire supply, but the opportunity has not occurred, so I am unable to give any information regarding them. With regard to Fig. 6, I should like to know from those who have this type of balancer working whether it has turned out satisfactory, or whether they have found any special troubles with it. I believe it has been in use for a long time. Mr. Cooper mentions static balancers dealing with 25 per cent. out-of-balance. I would like to have, if possible, particulars of a generator capable of doing a certain amount of out-of-balance, what the extra cost due to the static balancer arrangement would be, and how that extra price would compare with a motor balancer set of similar balancing capacity. Mr. Gray has raised the question of dealing with out-of-balance either by a local balancing arrangement or a central balancing arrangement. It appears to me that with a fairly large network it would pay to balance up locally instead of relying on all balancing being done at one central point. I think that has been done in Manchester. With regard to double-wound balancer armatures, I remember a case some years ago where the experience of these machines was most unhappy. Recently I have had double-wound armatures in use, and although the machines did manage to work occasionally, it paid me to scrap them after a very short life and put in a single-wound armature. Cross-connected shunt balancers are pretty well able to take care of themselves on the ordinary loads, but with cross-connected series windings, although the regulation is decidedly better, there appears to be trouble at certain times. Throughout the main portion of their work they are extremely useful, but if a shut down occurs, or a short between the middle and one outer, the balancer drops out and it will be difficult to start it again. To meet this contingency when there is only one balancer, it seems to me that there should be some switchgear arrangement for the machine in order to be able to put the two shunt windings in series across the outers, or else have the full voltage of the outers across the shunt of each machine, disconnecting the middle wire. If a short occurs between middle and outer, the excitation from that source of supply will cease, and in these circumstances it has paid us very well to have two balancers. The question of automatic regulators has been mentioned by Mr. Frith. It may be of interest to know that a couple of years ago I obtained quotations for such an arrangement, but it was altogether too costly, and I was obliged therefore to give up the idea. Mr. Atchison.

Mr. C. L. E. Stewart: I cannot help feeling what a very flimsy portion of an electricity supply the balancer is, compared with the rest of the plant. There may be fairly big machines supplying the load, and yet the whole supply is dependent on one or more small machines. The balancer shown in Fig. 8 is very complicated, and therefore Mr. Stewart.

Mr. Stewart.

undesirable. In the event of a short coming on, even with a very big station, the usual balancing capacity is so small that quite a lot of damage can be done in a very short time. A battery obviates this risk to a large extent. Mr. Cooper mentions the secondaries of the transformers in connection with the rotaries used as balancers. We have a direct-current 3-wire system and a high-tension 3-phase system. We use the centre of the star winding of the primaries of our step-up transformers which are supplied with current from rotary converters. The secondaries are mesh connected, and supply the 3-phase system. The rotaries act as double-current generators and balancers. I have not taken any elaborate tests on them, but so far they seem to have done very well.

Mr. Frith.

Mr. J. FRITH: With regard to the difficulty sometimes experienced in starting up a 3-wire balancer after a short circuit, if the field windings are excited in series from the outers with the middle wire connected to the blade of the common regulating resistance, this blade can be lifted, or moved on to an off point; the fields will then be given the correct polarity with which to start up again. No mention has been made of the various ways of accelerating the action of the balancers described for sudden loads, such as are typified by the Entz and Tirrell regulators. I do not know if the loads experienced in lighting work are sufficiently sudden to warrant this complication. I should like to know if the author has any experience with the various compound-wound voltmeters designed to show at a glance the pressure at the remote end of a feeder.

Mr. Barnes.

Mr. A. S. L. BARNES: A point not directly connected with the subject of balancers, but which a sentence in the paper has suggested to me, may be of interest to those present. The sentence I refer to is: "Frequent causes of out-of-balance current are arc lamps for cinematograph entertainments, but the author has declined to supply these except through motor-generators. . . ." Instead of a motor-generator for such work I would suggest the use of what may be called a motor-booster arrangement. I have never seen this arrangement described in any technical journals, though the fact of my having been abroad for over five years might account for that. Fig. B shows the suggested arrangement, the two armatures being mechanically coupled together, the machines being shunt wound. Two motor-booster sets arranged as above were installed some years ago on a system in which I was interested and have given every satisfaction, the

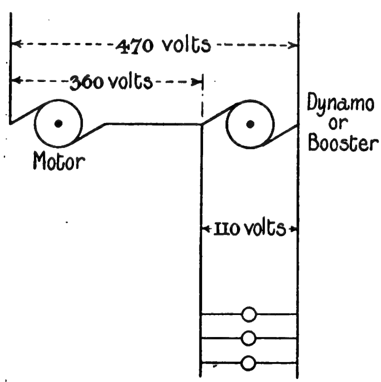

FIG. B.

machines were smaller and cheaper, and the efficiency of transformation was higher than it would have been had motor generators been installed. Mr. Barnes.

Mr. S. J. WATSON: I think that the best form of balancer for a power station is a battery divided into two parts across the 3-wire system left continuously on the mains. If adjustments are made so that a slight discharge is always being given, they will deal very well with the small out-of-balance which one usually obtains. The question of balancing cinematographs has been raised, and it may be of interest to state that I have got over the difficulty by running a short middle wire direct from the generating station to which the services to the cinematographs are connected, so that the disturbance which previously existed and which was liable to cause a variation in the supply pressure to other consumers is now entirely restricted to those users who actually cause the variation. When this can be done at a comparatively small cost, I am inclined to think it is quite the most satisfactory cure for the trouble. The actual cost of running this middle wire with four or five services was a matter of £70 or £80. I believe Mr. Atchison mentioned that the best practice is to supply at 440 volts from the outers and let the users cut it down to 60 volts. Under the Cinematograph Act, which has recently become law, it is permissible to take into the cinematograph-room a pressure above 100 volts, so that if the inspectors insist on the regulations being carried out, motor-generators will have to be used in all cases where the supply pressure exceeds 100 volts. A rather interesting point was mentioned by Mr. Frith concerning compound-wound voltmeters. It would be quite easy to make a voltmeter of that kind, but considering that many feeders which run from power stations are only 2-wire, and that the middle wire of the distributing mains may at times have to carry an appreciable balancing current, the reading of such voltmeters would not give a correct record of the pressure at the feeding-points. With regard to balancing machines generally, I may say that we originally put in a 2-machine balancer, shunt wound. Of course these machines did not automatically deal with out-of-balance currents, but were hand regulated. We also tried connecting the shunts, but found the results still unsatisfactory. We then carried out an arrangement similar to that shown on Fig. 3, where the whole of the middle wire balancing current from the network is carried round the poles of one machine in one direction and round the poles of the other machine in the other direction; this works very well. It has the disadvantage that in the event of a short between the middle wire and an outer the fuses will probably blow, but I don't think that matters very much if the battery is still on the busbars. It is very desirable that there should be a short-circuiting switch to cut the windings entirely off the balancers. A disadvantage of any balancing arrangement is that there is nothing to compensate for out-of-balances on any particular feeder, but only on the station balance as a whole. The question of static balancing, whereby connections to slip-rings are taken from direct-current armatures, has Mr. Watson.

Mr. Watson.

been mentioned by the writers of previous papers, but I am not altogether sure that it is advisable to interfere with the construction of the usual direct-current machine in order to get both alternating and direct current, because, as a rule, the speed and number of poles of a direct-current machine will not give a suitable periodicity to allow the alternating current to be used for other purposes in addition to balancing.

Mr. Cooper.

Mr. COOPER (*in reply*): Mr. Peck asks what I mean by the boosters taking 80 amperes 80 volts. Mr. Atchison touched upon that point, and what he said was practically correct. The machine described is a balancer to which two battery-charging boosters are attached. I gave particulars of them, as the armatures were mechanically connected, and therefore had to be considered in taking the consumption of the machine in order to allow for friction and windage losses. The question of kilowatts per hour was an oversight and should be units. In reply to his query as to 1 volt per 10 amperes it should be a difference, so that it is equivalent to ½ volt on either side of the mean. Dr. Garrard gave reasons which have practically been covered by Mr. Smith on the question of having a separate static balancer instead of using the secondary windings. The magnetising current was too small to operate the wattmeter I had at my disposal. Mr. Peck also called attention to the table of voltages taken on the static balancer. They were taken on ordinary instruments on the switchboard. I obtained other intermediate readings from 43 to 80, which showed a straight line, and therefore the readings are correct. With regard to the question of the balancer shutting down and reversing its polarity, this is overcome by having the shunts of the balancers separately excited through a shunt-breaking switch off the busbars; so that on running up again the polarity will be correct so long as the busbar polarity is right. This is the arrangement the author has in use, although not shown on the diagram. In reply to Mr. Gray, who asked if there was any load on the dynamo, the machine was slightly under half load. There were about 300 or 400 amperes on that machine when these figures were obtained. Mr. Gray apparently does not get nearly such good figures on his static balancers. These figures were questioned some little time ago in Glasgow in discussing the suitability, or otherwise, of static balancers. Whether I have got something special in the way of balancing I do not know, but these figures are absolutely correct as regards the difference in the current; they were taken on a good standard instrument. The change over of the station auxiliaries seems a little out of date. With regard to what Mr. Atchison has said, I had intended to look up the cost. The extra figure I paid for the machine was £130. The total cost of the combined set was £2,480. The plan of having balancers at all the feeding-points would mean extra labour, and what would be saved in cables would soon be spent in running costs. I find that the difference of the current of the two machines will always be alike, that is to say, the motoring armature will have 16 amperes more than the dynamo end,

Mr. Cooper.

In other words, it takes double the current at half the volts that it takes to drive the machine light. If it is desired to boost the out-of-balance side, a mid-wire booster can be attached, as shown in the last diagram, although I do not consider it necessary if a difference of only 2·5 volts can be obtained with an out-of-balance of 80 amperes. Mr. Stewart remarks about balancers being flimsy. I have not found it so in my case. It would not pay to run a balancer of such a capacity that it could deal with heavy short circuits, and the same objection would apply to having dynamos also of such capacity. Mr. Frith asks about sudden loads. In small stations like ours we do not cater for them, but if compelled to supply we put them across the outers. The ordinary out-of-balance loads that come on the balancer deals with quite satisfactorily. In reply to his query regarding special voltmeters for recording the voltage at the end of the feeder, such instruments are made, but they do not give the actual voltage, they only give the calculated voltage, by having a series winding acting against the shunt winding. This complication can be avoided, and the same results obtained by having a table of voltages for the given loads. Mr. Barnes has sketched a motor-generator for cinematograph work, which possibly might save a little in efficiency over an ordinary motor-generator, but it is certainly more complicated. I have two cinematograph entertainments in Colne, and have put in motor-generators, and they answer extremely well. In reply to Mr. Watson, the motor-generators cost from £50 to £60 each. It was quite impracticable in our case to run a special wire as he has done, as they are a long distance from the generating station, and I do not quite understand how it can be done except by taking a tapping off the battery or running a special balancer. I do not consider a static balancer complicated, as it only needs slip-rings on the dynamo.

SOME NOTES ON STANDARDISATION OF ELECTRICAL MACHINES.

By R. ORSETTICH, Member.

(*Paper received from the* BIRMINGHAM LOCAL SECTION, *February* 9, *read at Glasgow on March* 8, *and at Birmingham on March* 9, 1910.)

The last papers dealing mainly with the manufacture of electrical machines were those of Messrs. Scott and Esson in 1903, and they had in view principally the construction of large machines. Since that time a large number of important developments have taken place, which, without causing any striking departure, have changed very considerably the position of the electrical industry. Amongst the most important ones are those connected with the increase in speed and output which made the present turbo-generators possible, the adoption of the interpolar and compensating windings which have now become a normal feature of continuous-current machines, the advent of the single-phase commutator motor for power and traction work, the several electro-mechanical systems of balancing fluctuating loads which are employed for winding gears and rolling-mill service, the use of separate forced ventilation on large units, together with the adoption of special steel alloys for the laminations, and many others. The least apparent, however, but one of the most important steps, appears to me to be the improvement in the nature and systems of insulation and the far greater care taken in the execution of all details, which has resulted in making the present electrical machine a thorough mechanical unit.

The price of all classes of electrical machines at the same time has been reduced considerably. The price of the materials, and especially of copper, has risen considerably in the last ten years, and it is therefore apparent that the reduction in price must have been brought about only through improvements in the design and in the arrangements for the manufacture. Increased competition having on one hand reduced greatly the profit, but on the other having increased almost in the same proportion the cost of the commercial departments required to obtain the orders, the percentage of the price required to cover these two items has remained practically the same.

The author proposes to discuss mainly in this paper some of the arrangements generally adopted for production, as numerous papers have been published from time to time dealing with the changes and improvements, purely from a designer's point of view. The continually increasing field for the use of electrical machines, and the competition for new markets have necessitated the adoption of new

measures in the design and manufacture, so as to make the machines comply with a large number of various requirements and stricter specifications, and at the same time enable them to be produced cheaper and better. The sum of these various measures is commonly included under the headings of "Standardisation" and "Production in Quantities."

The standardisation consists in selecting for manufacture a definite number of types and sizes as answering average requirements and in designing them in such a way that they are eminently suited for production in large quantities. All details of these types must be fixed so as to make it possible by partial modifications to fill requirements of special conditions with the minimum of alterations to patterns and stock, and therefore with the minimum of expense.

The production in quantities has the object of reducing the cost connected with putting the machine through the shop by distributing this cost, which is up to a certain extent independent of the quantity over a large number of machines. This cost comprises office work, such as designing, drawings, issuing of instructions to the shop, the cost of procuring, inspecting, and testing the materials, the making of special tools and the setting of these tools to work. The general shop management expenses and the inspection and testing of the finished products are also included to some extent. The manufacture of large quantities of the same type also enables the shop to acquire the materials in larger lots and therefore in the most suitable market, with consequent reduction in cost. It further enables the shop to adopt all modern methods of checking interchangeability of parts by the use of limit gauges and jigs, which would be too expensive if only a few machines were made. The flow of materials through the shops can be arranged in a uniform way so as to keep all departments equally busy. The benefit of keeping one's workmen constantly employed on the same line of work shows itself in the increased skill they acquire in the performance of the operations or in the handling of a given machine. The time required for the work is in this way reduced to the minimum, as well as the time lost in between operations, and the efficiency of the machine tools becomes higher, whilst the man at the same time obtains part of the gain in some form of bonus for his extra exertion. There are, however, several disadvantages which must be considered, such as reduced flexibility in the manufacture, which makes very troublesome and undesirable any alteration from the standard, however small; also the longer time required for producing any new article owing to the necessity of making samples to avoid errors, which would be multiplied into very large figures.

The requirements of the market being of a fluctuating nature, it is impossible to fill the demand otherwise than by estimating the average requirements over a period corresponding to the time necessary for the manufacture of the goods. From the above it follows that the conditions for carrying out successfully the production of machines on a large scale should be:—

1. To manufacture for stock only and not for individual orders.
2. To have as few types as possible and to use as many parts as possible in common amongst the different types.
3. To concentrate the aim of the design in the production of perfectly interchangeable and mechanical details, even if the cost of machining is somewhat high, with a view to reducing the cost of assembling the different parts, which can only be done individually.
4. Regularity of the demand of the market.
5. Even and continuous supply of raw materials and labour.

Commercial Considerations.

The requirements of the selling side of the business have to be taken into careful account when fixing the basis of a line of machines. This usually offers great difficulty, as it is generally found that they are almost in direct opposition to the requirements of the shop. A compromise has therefore to be arrived at embodying the most important propositions from either side.

1. *Number of Types.*—The salesman in his daily touch with competition requires the number of types which he can offer to be kept as high as possible, so as not to be underbid by another salesman offering a type which comes nearer to the requirements of the client. The shop will find that this necessitates a much larger capital outlay in stock and plant and a much smaller turnover on each individual type than if only a small number of different patterns should be adopted. The designer will find it to his advantage to agree as far as possible to the large number of patterns, as it will be easier to find in every instance a suitable type to fill any specification, and also because it will have the effect of reducing the number of alterations to standard machines. The recommendations of the Standard Committee, who went into this matter very thoroughly, have unfortunately not met with complete success, because they reduced the number of sizes below what had been accepted as normal practice by a number of firms. These, having already gone to the expense of producing a larger number of patterns which represented a large investment, could not agree to this reduction, so that at the present moment most firms still manufacture many more sizes than are mentioned in the Committee's report. My experience is that for a line of standard continuous-current machines between 1 H.P. at 2,000 revs. per minute and 100 H.P. at 1,000 revs. per minute there are usually employed from eighteen to twenty types, and practically the same number for a line of 3-phase motors between 1 H.P. at 1,500 revs. per minute and 100 H.P. at 750 revs. per minute. These numbers are based on an approximate output of some 500 machines per year of the smaller size up to about 25 machines per annum of the larger size. Of course, should the expected yearly turnover be less than this the number of types would have to be reduced somewhat, so as to keep the initial expendi-

ture within smaller limits. For the splitting up of machines of larger outputs into types technical considerations are more decisive, and these will be discussed later on.

2. *Delivery*.—A few standard types should be always available for immediate delivery. This necessitates the keeping of a stock of fully finished machines wound for current voltages and speeds. This does not offer any difficulty in connection with continuous-current machines, as the great majority of the supply companies and corporations have arranged their mains on the 3-wire system, with 460–500 volts between the outers. Motors up to 3 H.P. are allowed between an outer and the neutral; larger sizes must be connected on the full voltage between the outers. With the addition of a few larger motors up to 25 H.P. wound for 230 volts as required by small independent plants, the stock is quite complete. With alternating current the matter is very much more difficult, as one has single-phase, 2-phase, and 3-phase supplies, the voltages of which vary considerably as well as the frequency. For 2- and 3-phase plant, the most usual ones appear to be a voltage of 440 and a frequency of 25, 40, and 50. For single-phase the matter of fixing a stock is almost impossible, owing to the frequencies ranging between 25 and 133.

Next in importance is the delivery of semi-standard machines—that is, machines which are obtained by adapting the ordinary type to special requirements, such as special voltages or abnormal speeds. This would be effected either by winding a standard armature or field with a special set of coils, or by fitting a longer commutator to an otherwise standard machine.

3. *Flexibility of Types*.—As it is a most difficult matter to fix the exact amount of power required for performing certain work, and as this might even vary at different times of the day, machines have to be made with ample margin in all directions—viz., mechanical strength heating, sparking, wear, etc. The recognised six hours' run with a definite temperature rise, whilst it is perfectly sufficient to cover the responsibility of the designer, does not help the salesman whenever a client finds that the motor is just below his expectations. Shunt regulation in continuous-current motors, together with overloading capacity, is one of the points which offers most of the difficulties.

4. *Special Machines*.—These cannot be entirely avoided, as it is impossible to make standard machines cover the entire range of applications. It is a most complicated question to inquire into the extra price that should be charged for the making of an entirely special machine. This price should not only cover the expense of design, drawings, and patterns, which are usually included, but the extra attention required in following it through the shop, the delay caused by stopping important work at the machine tools, the extra adjustments in fitting a new design together, and the risk of alterations after test, due to its novelty. The whole of these items cannot be expressed in figures, and can only be guessed from experience, and for this reason it will be impossible to persuade any one not connected with

actual manufacturing that such jobs are hardly desirable from the turnover and profit point of view. Even if a firm does not wish to undertake this kind of work, it will sometimes be unavoidable if special machines are required in connection with large contracts for standard work. It will therefore be in the interest of the designer to keep the standard types always in front of him when dealing with this kind of special pattern, so as to reduce the expense for new parts to the minimum and at the same time give a reasonable delivery. As examples, one could quote a 25 H.P. continuous-current motor for 100 volts and 2,800 revs. per minute, as often required for driving centrifugal pumps.

The Store Department.—Successful manufacture is necessarily based on the smooth operation of the department concerned with the supply of raw materials, and it will be well to begin by considering the organisation of the store department. Exact knowledge of the position of this section of the works will enable the designer of the machines to move within practicable and economical limits as much as the correct knowledge of the requirements of the designer will enable the storekeeper to run his department as a really useful auxiliary to the shop.

(*a*) *Materials.*—The materials to be kept in stock have to be fixed by the engineers with reference to the nature and extent of the manufacture, and a schedule of standards has to be drawn up stating the number and quality of the different materials; of each kind a definite number of varieties only is accepted, and no deviation is allowed from these unless special permission is obtained from the management. Charcoal iron sheets, for instance, will be kept in stock in certain thicknesses only, say of 16, 19, 24, and 29 S.W.G.; copper and brass rods in standard-drawn sections of $\frac{1}{8}$, $\frac{3}{16}$, $\frac{1}{4}$, $\frac{5}{16}$, $\frac{3}{8}$ in. etc., in diameter. Special sections which are not obtained in the trade should be avoided whenever possible, but if indispensable, their number should be definitely fixed and rigidly adhered to.

In a similar way tables should be prepared for steel bars, mild steel keys, copper sheets, micanite, fibre, etc., bolts, screws, nuts, and rivets require similar limitations, not only as regards size, but also as to length; copper wire should be distinguished in bars and insulated, and the latter again in two or three sections according to the thickness of covering, braiding, etc.

At the same time, specifications have to be prepared giving full particulars of the material, the tests to which they have to comply, and the limits for their acceptance. The inspection of incoming materials is no light task for the storekeeping department, and in large works requires a wide experience and often scientific training, this all the more as the inspector has very often to exercise his own discretion as to the advisability of accepting certain material, which might not be to the letter of the specification without being faulty, and the rejection of which might seriously handicap the shop output.

(*b*) *Amount of Stock.*—The variety of materials required excludes

the possibility of individual attention to the oscillations of the amounts kept in stock. The stores must therefore work on a basis of automatic replacement, keeping the idle stock down to the minimum without running the risk of not being able to supply the current demand. This is done by fixing maximum and minimum limits of stock. The maximum is settled on practical considerations of the value of the stock, and the smallest amounts which it is advisable to put on order at any time. The minimum limit is fixed on the basis of the time required to replace the material so that a zero stock should not be reached under any conditions. These two limits cannot be taken in any way as absolute quantities, but must vary according to the conditions of the sales of the finished machines. It is therefore important that the limits should be revised periodically, and for this purpose it is advisable to show on the cards, on which the oscillations and the positions of the stock are usually entered, the amounts used over regular periods of any three months. By glancing at these totals, it is possible at any moment to see whether the demand for a certain piece is increasing or decreasing, and this shows at once whether a revision of the limits is required. A point of importance in settling the numbers which have to be kept in stock is the consideration whether a certain part will be used in the form in which it is stocked or whether it is to be subjected to further modifications limiting its range of application. For each frame of a machine, for instance, which is used in the form in which it is kept in stock, it would be necessary to keep in stock two or three armatures, because these are intended to be stocked wound for different voltages.

(*c*) *Stock in Progress of Manufacture.*—In addition to raw materials a large quantity of the stock consists of half or fully finished parts, and this kind of stock can be kept in three different ways :—

1. Only parts which are common to several types being built for stock, all other parts being manufactured to fill a definite order.
2. A more advanced stage is when in addition also parts belonging to individual types are manufactured in advance and kept in stock, because of their requiring either a long time to obtain the material or because the machining has to be done with special care or with expensive appliances. The windings of the machines would also come under this class.
3. The third stage, and the most complete one, is when all parts without exception, belonging to any of the machines manufactured, are kept in stock, so that all machines are assembled complete from the components. The third stage, of course, is the ideal one, but is only possible when there is a large demand for entirely standard and identical machines.

The usual condition for an average factory would be corresponding to stage No. 2, because this combines the advantages of a fairly flexible

system with minimum expenditure. The parts are made up to a point where they can be worked in either for an entirely standard machine or for a special type, or, on the other hand, any part can be omitted from a standard machine so as to make it answer to a particular specification, such as, for instance, the manufacture of a line of continuous-current motors, where the complete shells, shafts, commutators, brush-gear, terminal-boards, and armatures are each kept in stock, to be assembled into standard machines whenever the occasion arises, and where at the same time a special longer commutator for a lower voltage can be used when required without necessitating any other alteration but a change of the commutator itself and the brush-gear.

One of the points of great importance in dealing with standard or semi-standard machines is that whenever an alteration is required in a standard design for any reason, the machine has always to be assembled from components, and the alteration must not be done under any conditions from a finished machine. This because, first, the parts which are substituted have already been used once, even if only for assembling, and therefore cannot be regarded as new parts; secondly, because it is difficult to watch that these are returned to the storeroom in good condition; and finally, and above all, because the cost of assembling the machine originally and of disassembling for the alteration will be entirely lost.

Another question of importance in the handling of stock parts is to be found in the method of allocating the stock to the different orders. This can be done either by entering on the stock card a requisition for the number of parts to be used for a certain order, and regarding these parts as being appropriated for this order whilst they are remaining on their shelves. In this system the "minimum" quantity might be reached on the card at any time, whilst a larger number of parts still exists in the stores. The other system consists in removing the parts as soon as requisitioned for an order to a different part of the shop where all items belonging to a certain order are collected. This second method has the disadvantage of requiring an additional handling of the material and of tying up parts beforehand and in advance of the time when they are actually required. The expenditure for stock is therefore higher than with the other method, but at the same time it is safer, as it makes absolutely certain of the parts being in existence and not only on paper.

Mechanical Considerations.

In dealing with the standardisation of a new line of machines the subject can be divided into two sections: one containing general measures affecting all sizes, the other dealing with the arrangements for making any one machine most suitable for the conditions of manufacture already explained.

The considerations of the first kind must be affected by the extent of the intended manufacture, as a very thorough and rigid standardisa-

tion of every part individually can only be carried out if the number of machines to be produced is very large. In the ordinary course for an average manufacture of a few hundred machines of each size per annum the main consideration will be to keep the cost of patterns and tools within reasonable limits, and to try to use the same part over again in common for different sizes.

General Standardisation: (a) Diameter of Bore.—This will be fixed as a starting-point of the whole line of machines and will be based on the most suitable dimensions to obtain a given output. The length of the core will have to be settled at the same time, and here the great question arises as to whether there should be one or more lengths of cores for each diameter. For continuous-current machines where the types of the frame and the number of poles are settled beforehand, it is always advisable to have a separate diameter for each length unless the manufacture is very small indeed. For alternating-current machines, where the same frame can be used for two or more lengths of core or different numbers of poles, it will be quite satisfactory to reduce the number of diameters and obtain the required number of types by having two lengths for each. The longer one can preferably be used for a smaller number of poles than the narrow one.

(*b*) *Commutators.*—The length of the commutators should be made sufficient to carry the amperes corresponding to a voltage of 230, with the maximum output allowed for in the standard list. As commutators are intended to be kept in stock as finished articles it will not be advisable to reduce this length when the motor is supplied for higher voltages, especially as the excess in length will be reduced when narrow brushes are used for a higher voltage. The question of using a longer commutator than standard for very low voltages has to be considered, and space has to be allowed for this purpose on the shaft of the machine.

(*c*) *Slip-rings.*—The position of the slip-rings of a line of machines has not been finally agreed upon by designers. It would appear that the best position would be in a place corresponding to the commutator on continuous-current machines, but as the connections between the winding and slip-rings cannot be made in the same simple way, and as there is a great chance of dust lodging itself in between adjacent rings working with high difference of potential, it appears that it is very advisable to fix these on the outside of the bearings and to carry the connections through a hole in the shaft. In this way they can always be easily cleaned and inspected and made enclosed or protected as the case may be. The shaft length between the bearings is not increased, a point which is of great importance in view of the very small clearance between stator and rotor. As a disadvantage must be mentioned that the shaft cannot be extended on both sides as required sometimes for crane motors.

(*d*) *Small Parts.*—Small parts, such as terminals, brush-holders, spindles, insulating bushes, will be always arranged so as to be suitable

for several types. The terminals will either be arranged individually on small pedestals and assembled on any machine to suit the current, or else on standard slate slabs, classified by the current which they can carry. The centres of different slabs should be kept the same, so that any machine could be fitted with a heavier or lighter terminal whenever the winding specification is issued.

Individual Standardisation: (a) Frame.—The frame, made of cast-iron for the sake of quick delivery, should be shaped in such a way so as to be suitable for use as a semi-enclosed machine—that is, one in which the openings over the commutator and at the shaft end are left without any further protection. It must at the same time be suitable for conversion into a protected machine by the addition of small stamped or perforated covers, which prevent the entrance of foreign matter. These covers will be of the solid type whenever the machine has to be used as enclosed. Two further varieties would be the "enclosed ventilated" and the "dust-and-gas-proof" one. The first is a machine where the openings are shaped so as to prevent the entrance of water or rain, and can be produced without requiring any structural alteration of the standard frame. The second one in late years has been abandoned in favour of the "explosion-proof" type, the experiments carried out with several makes having proved that it is impossible to prevent the entrance of gas into a machine, however well enclosed, and that in cases where this is dangerous the only protection is afforded by making the frame with accurately machined joints and sufficient mechanical strength to withstand an internal explosion. A specification of this kind, however, requires the making of an entirely special pattern, and cannot be provided for in the standards. The construction of the frame is also affected by the question of the commutating poles, which are often required to be added. In machines with fairly large diameters it will be still possible to retain round poles, which are the most economical as far as weight of copper is concerned. The commutating poles will then have to be fixed either on flat facings provided on the inside of the shell and bolted on from the outside, or else will be secured by means of one large central bolt forged in one piece with the commutating pole. In the case of machines where the pole-pitch is kept rather small, the addition of commutating poles will make the space for the winding of the main poles so restricted that it will be necessary to adopt a square section of poles, and therefore square field spools. The most suitable way to make these poles will then be to assemble them out of laminations in a similar way to what is done for the poles of synchronous machines. This would be all the more advantageous if there are two lengths of core for each diameter, because one die only would serve two machines. The method of fixing this type of poles as well as the commutating poles will then be by machining all round the internal cylindrical surface of the shell, and bolt the poles to it from the outside. This method will result in a slightly increased expenditure on the labour for fixing the poles, due to

the fact that it is not advisable to cast-weld the laminations in the iron of the frame, as is often done for round poles, but it will reduce in its turn the charge for fixing the commutating poles as well as do away with the cost of making separate pole-shoes, these being punched in one piece with the pole itself. A point to be considered in the settling of details of the frame will be the advisability or not of having an entirely open frame, with bearing of the pedestal-type to take the place of the protected-type machine. This is very often required, especially for direct-coupled sets, on account of the better ventilation and the easy access to all parts as well as because of the better appearance of the unit in itself. As there is not a very great sale for the last type of machine, it would not be advisable to have a duplicate pattern for all sizes, but it will be sufficient to start from units of some 12 in. to 15 in. in diameter, both for continuous-current and alternating types.

(*b*) *Bearings.*—The recognised type of bearings for small machines is the "shield" type, in which the bearing itself is fixed on a spigot all round the frame by means of bolts. The first question to settle will be the diameter of the bushes, namely, whether both should be alike and interchangeable, or whether the one at the driving end should be stronger than the one at the commutator end, respectively at the slip-ring end. After some consideration it will appear that, both from the customers' and from the manufacturers' point of view, it is advisable to keep both bearings alike, as the saving in using a large and small bush is hardly worth mentioning. The bushes will be conveniently made of phosphor bronze, as they offer the least wear combined with minimum of weight. They can, however, be made in white metal for diameters above 3 in. The bushes will be fitted with suitable oil grooves on the top half and with draining rings at the two ends so as to prevent the oil from creeping along the shaft. The bolts holding the bearings must be arranged in such a way that the bearing can be turned by 90° or 180° when the motor is required to be fixed to the wall or ceiling. For this reason it will not be advisable to cast the feet of the machine on the bearing brackets, as is done by some firms, even if this might result in a slight saving in the price of the frame. If the feet are on the bearings, to avoid the necessity of supplying new castings whenever a different position of the feet is required, it will be necessary to turn round the bearing bush together with part of the bearing centre carrying the oil well, but this, besides being an expensive arrangement which will wipe out the saving in the shell, will also carry with it the danger of oil leakage from the joint. A great advantage will be found both for manufacturing and storing in making the two end shields of the machine alike, and this both for alternating- and continuous-current types. In this case the frame will be made perfectly straight or slightly curved to give a pleasant appearance to the machine, and the two bearings can be of the shield type of the same outside diameter as the frame. In another design they are made in the form of small discs and the frame is brought down at the two

ends to the diameter of these discs. Both constructions are equally satisfactory, but the first one is very much stronger and affords a much ampler space all round the commutator. A similar construction can be adopted for 3-phase machines, and especially if the slip-rings are placed outside the bearings. Some firms adopt the plan of putting the slip-rings inside the bearings for the purpose of using the same type of bearing brackets for the continuous-current machines and for the alternating ones. This has a good deal of attraction from the stores point of view, and should be recommended excepting for the objectionable position of the slip-rings. The main point claimed—viz., the reduction in cost of patterns—cannot weigh much, as a duplicate set of patterns would be required if the output in these types is at all large.

(*c*) *Reduction Gear.*—This is an addition which is very often required to standard machines, and provision must be made in the standard design for it. The usual way is to fix a set of bearings cast in one piece on bosses provided on the outside of the frame. These bosses, however, have to be cast on specially, so that a small stock of frames will have to be carried on this account. The best arrangement from the manufacturing point of view is to fix the countershaft of the reduction gear on a separate stool fitted with two bearings and to mount the motor on this stool. The two bearings can be taken from a standard machine of larger size. The space taken for the combination is the same as taken for the plain motor, but the method has the disadvantage of being rather expensive, and of raising the centre of gravity of the motor from the floor-line. A third arrangement put forward by some makers is to fix the countershaft on two brackets which are fixed to the outside flange of the bearing brackets. The distance between the bolts for fixing these brackets can be the same as the distance between the bolts for fixing the end shields, so that the countershaft can be rotated round the motor in a number of positions. In this construction, of course, the body carrying the self-oiling bearings of the countershaft must be rotated round so as to bring the oil well always into the vertical position. The advantage of construction of this kind would be that the countershaft could be fixed on the machine at any time after it has left the shop without requiring any structural alteration.

(*d*) *Spider.*—The necessity of adopting a spider in the armature has been debated very often between different designers without a definite conclusion being arrived at. There is no doubt that there is some advantage in having a spider to which to fix the stampings and the commutator, so that the shaft can be withdrawn at any time, either for repair or to exchange it with a shaft of different dimensions; but at the same time it must not be overlooked that the adoption of a spider carries with it great inconvenience; for machines with an inside diameter of the stampings of 10 in. or less, the addition of a spider would mean an extra expense, as the value of the stampings which are saved is not sufficient to balance the expense in material

and labour in making the spider. Also in smaller types the thickness of the centre boss of the spider will become so small that it will be hardly possible to make it in cast iron satisfactorily and this will necessitate making it in steel. The ventilation of the stampings of the armature will be particularly handicapped by the presence of a spider, and the diameter of the commutator boss will also be increased to admit its being mounted on to the extension of the spider, so that there will be hardly any space left for ventilation. From the manufacturers' point of view no spider should be used up to an inside diameter of stampings of 10 in.

(*e*) *Terminals.*—Apart from the question of the size of the terminals which has been already mentioned, the position of the terminals requires some consideration. The best solution would be, no doubt, to have a special recess cast on one side of the machine and to protect by means of a cast-iron cover the terminal board in this recess. This, however, means that the position of the terminals will not be flexible, as it should be, and might cause great inconvenience if the motor should be fixed, for instance, close to a wall with the terminal boards towards it. The fixing of the terminals on the top of the machine will not solve the difficulty, because on the one hand it interferes with the position of the eye-bolt, and on the other it makes the terminals come on a horizontal line, or at the bottom, if the machine is fixed to a vertical wall or to a ceiling. The last mentioned position would be a very awkward one, because it would make any oil which might find its way out of the bearing run into the terminal box. Some makers have selected the top of the bearing shield, which has to be turned round when fixing the motor in any way out of the normal; even this position, however, might be unsuitable if the space where the motor has to be placed has very restricted headroom. The solution will be found by using independent terminals fixed to small pillars which can be mounted, as a standard way, either on the top or on the side, and which can be shifted without great difficulty whenever a special occasion demands it. Another method which has been adopted very often is, not to have any fixed terminals at all, but to end the leads into loose split sleeves, shaped so as to build a sweating socket for the cables of the supply. After connecting up, each sleeve is insulated by itself by means of a tube slipped over it, and the three or four cables are bunched together into one group, which can be protected either by a large conduit pipe or any similar appliance. This method can be also adopted with advantage with totally enclosed explosion-proof motors, the only alteration being that instead of using bushes at the point where the cables leave the frame, it is necessary to use gas-tight glands.

(*f*) *Brush-holders.*—The design of the brush-holder lends itself better than any other part to thorough standardisation. Although any type of well-constructed brush-holder will be found perfectly satisfactory, the opinions of the users are divided very much between two classes: *i.e.*, the one in which the brush-holder is tightly gripped at the

end of a long arm hinged on a spindle, and the other in which the carbon is free to slide between two guiding surfaces carried rigidly from the current-collecting gear. It will therefore be advisable to arrange for both types of brush-gear to be exchanged for one another whenever required. Both types of holders should be also designed so as to allow satisfactory running of the commutator in either direction and fairly noiselessly. They should be further suitable for different thicknesses of carbon blocks as might be required to suit the different voltages, and provision should be made to prevent the loose arm of the brush-holders from dropping on to the commutator surface in case the carbon should wear away entirely. The construction should be such that the wearing surface of any carbon can be examined at any time, and the carbon removed if necessary without disturbing the others. The current should be collected from the carbon to the brush-holder spindle without passing through any hinged joint.

Standardisation of Large Machines.—The general standardisation of large units cannot be carried out to the same extent as for the small units, on account of the fact that only a few of these types are usually required, and that the specifications for these vary to a very considerable extent. It is, however, quite possible to institute a system of sizes independently of any particular output, and to select the most suitable size out of this series when estimating or when executing any order to a specification. It will often happen that the type selected is slightly above the requirements, especially as regards weight, but the apparent loss which might be incurred in using this would be amply equalised by the saving in design, patterns, and tools.

A standard series of direct-current machines is started upon by fixing certain standard diameters of bores, which, beginning with, say 25 in. or 28 in., will extend up to, say, 120 in. by differences of 4 in. to 5 in. in the smaller sizes, up to 10 in. in the larger ones. In this way one will obtain some fifteen different sizes, and as the length of the core can be made of two different dimensions, say 10 in. and 14 in., the result will be a line of thirty standard types, which should be quite sufficient for ordinary requirements.

The stampings for these machines will be conveniently made in sectors, and for this purpose the periphery will be divided into six, eight, or twelve equal parts, and a standard set of blanking dies will be provided for these. The spiders for the armatures will be made with a suitable number of arms to correspond to the sections of the armature stampings.

In settling the dimensions of the frame one could keep the flux per pole practically constant or increasing very slightly only, and increase the number of poles in proportion to the diameter. This practice is quite suitable for slow speeds, as used by Continental makers, but has the disadvantage of giving too many bars on the commutator when using lap winding. It will therefore be advisable, in order not to obtain machines which are too light for large outputs, to increase the flux per pole at the same time as the number of poles. As long as

commutating poles were not used it was important to increase the number of poles considerably for machines of low voltage. Since the adoption of the interpoles has become less necessary, as the heating of the commutator is very much less than before, and there is not the slightest difficulty in commutating some 600–700 amperes per spindle, whereas 300 amperes was the average previously. If laminated poles are decided upon, a line of standard dies will have to be arranged to correspond to each armature sector. Any of these could then be also used amongst different machines, whenever it should be found that a more satisfactory design could be obtained by using a stronger or a weaker flux per pole. Of course, whenever a stamping obtained from a die not belonging to the respective type is used, it is necessary to bore the inside and the outside of the poles to obtain the correct curvature, but if this is done for a single design only it would only affect very slightly the cost of the machine, whilst it will save the expense of a new die.

The line of commutators will also be settled independently of any output or current. The diameters will be fixed with gaps of 3 in. to 5 in. in between, and an average length of 1 ft. will be taken corresponding to about 300–400 amperes per spindle. As the two end rings will be made of steel and independently from the body of the commutator, should any additional length be required it will be sufficient to lengthen the rim of the spider of the commutator, which can be done at very slight expense. It is most important to adhere rigidly to the dimensions of the clamp rings because any change of these will mean a new set of micanite moulds for the V-rings of the commutator. It follows that whenever a special wearing depth of the commutator copper is specified, the extra amount will have to be added on to the standard outside diameter of the copper bars and not from this diameter inwardly, although a certain extra expense for copper is thus incurred.

The bearings of such a line of machines will also be fixed in standard sizes in steps of ½ in. in the diameter. They will be about 2½ diameters in length, and will be fitted with automatic ring lubrication. The best arrangement would be to select a large centre height, so that whenever a smaller centre is required an additional temporary flange is fitted to the pattern and the remaining is stopped off in the moulding. This is done very economically if a large core box is put in hand from the first, with which any length of core can be obtained for the stopping off, and in this way in many instances an expensive new pattern will be saved.

Another considerable item when dealing with large machines is the bed-plate. The patterns for these can be reduced greatly by settling on standard sections, and making up the bed-plates in a square with round corners, and cutting it up at right angles into four parts, so that four patterns of the four corners are obtained. By fitting distance-pieces of suitable length bed-plates of any dimensions can be obtained with very little expense. In some instances, for types which are used

very often it will even pay to make these standard patterns in iron, in order to prevent deformation.

The brush rocker-gear, which, for small sizes can be fixed on the bearing, and which on larger sizes is usually carried from the magnet yoke, can be standardised on the same lines as the shell. It will be necessary to arrange the ring in such a way that more or less arms can be fitted to it without inconvenience, according to the number of poles selected for the machine at any time. Some means of adjustment will also have to be provided for raising or lowering the arms carrying the spindles, so as to allow for different wearing depths on the commutator, or, when the diameter on the commutator is exceedingly small, for a different type of arm.

The terminals and cable connections will be easily standardised by selecting a series of flexible cables for all currents up to 600 amperes, and by using 2, 3, or 4 of these in parallel so as to be able to deal with currents up to, say, 2,400 amperes. The respective sockets will be then fixed together with suitable insulating bushes, and supported on independent pillars. Any combination of these will then be possible, and they will therefore cover the range of shunt, compound, interpole, or compensated machines.

For large alternating-current machines a similar system of standardisation can be adopted. A line of diameters is settled upon, but in this case more latitude is allowed on account of the possibility of varying the length of the core without affecting the pattern of the frame or of the magnet-wheel. In this way between a diameter of 2 ft. and a diameter of 10 ft. approximately 12 diameters will be found sufficient, the gap in between the smaller sizes being approximately 5 in. and the larger ones 12 in. On account of the varying number of poles to suit the various periodicities and speeds, it will not be advisable to make complete dies for the stampings of the stator, but it will be more suitable to arrange independent cutting dies for each diameter, viz., one for the inside diameter and one for the outside, these to be so made that any combination of cutting dies can be arranged for, so that either very deep or very shallow stampings can be produced. The shells themselves will be best made without fixed end-plates so that these can be shifted further in or further out according to the width of the laminations, and without necessitating new patterns or alterations to the core boxes. The poles should be made out of stampings, and here again a line of standard poles can be conveniently designed to suit a number of pole-pitches varying between 7 in. and 14 in., which, assuming a periodicity of 40 or 50, would give all combinations between the very slowest and the very highest speeds, as well as average dimensions for poles for 25-cycle machines. Any of the dies for these can be arranged to suit a wide range of machines, but, of course, whenever pole stampings not belonging to the correct curvature are employed it will be necessary to bore these out on the inside surface and turn on the outside.

All the mechanical details such as bearing, foundation-plates, guards,

and terminals provided for the continuous-current machines, can be easily worked in to suit the alternating-current machines.

Electrical Considerations.

Most of the arrangements explained previously are really limitations of the freedom in the electrical design. They are, however, necessary for the economical production of the machines and have been recognised as such by all makers. The art of practical designing for manufacturing purpose will therefore consist not in fixing at haphazard in every instance the very best dimensions that can give the correct output, efficiency, regulation, and temperature rise, within a certain specification and at an apparently satisfactory price, but in trying to obtain a design which will give an equally satisfactory commercial machine, made up with existing elements, patterns, dies, tools, etc. The reason for this is that the "cost price" of a machine includes often a factor of considerable uncertainty, namely, the percentage for general expenses, which is very often supposed to cover the cost of patterns and tools. As this percentage can only be fixed on the assumption of an average expenditure on this account, it will be apparent that unless a continuous check is exercised on the expenditure a heavy loss might be the result at the end of the year if the stock of patterns is booked at their correct low value, although every cost might have shown a satisfactory return. On the other hand, the alternative way of charging to each design the full cost of new patterns and tools would result in making the cost price of a machine so high that it would be most difficult to obtain any orders. Against this it is clear that there is a great advantage in fixing the number of patterns and tools as far as possible beforehand, and arrange the general charges for them in such a way that they can be distributed on the average number of machines produced during the year. On account of the slight handicap in arranging the design a slightly smaller margin will be available in some directions, and more attention will have therefore to be paid to the quality of the materials employed and to the execution of all details. That this is quite sufficient to make up for it is proved by the fact that there is not a large successful factory in which these conditions have not prevailed. Thus the adoption of two lengths of core for each diameter is no doubt a disadvantage from a purely electrical point of view, as for each output, strictly speaking, there is only one diameter and one length which will give the best proportions. When using a long core as required for laminated poles, it will be found again that this is not quite as satisfactory as a round core, but if in order to obtain a suitable ratio to give the room required for round poles one had to go to the expense of adopting a much larger diameter, there is no doubt whatever that the little sacrifice in the electrical design will be fully repaid in the cheapening of the production of the machine and in increasing its field of application, apart from the fact of a better efficiency obtained with

the machine of smaller dimensions. In alternating-current machines the inducement to use long cores would be larger than for continuous-current machines, but the effect of the length of core will have to be accurately investigated on account of the altered conditions of the leakage. This will, however, be met best by adopting machines with long cores for fewer poles, and narrow machines for slow speeds, as they have necessarily a shorter pitch.

The stampings of the continuous-current machines should be arranged for one, or at the maximum two numbers of slots only, and these can be provided with such a wide range of windings as to cover all practical requirements. The number of commutators for a given type of stampings should not be more than two at the most, and should be arranged in such a way that the higher number of bars can be used for 500 volts with the slowest speed, and, therefore, with the largest number of turns per commutator bar, and the lower number of bars should be still sufficient to give the highest speed at the lowest voltage, *i.e.*, when the number of turns per bar is the lowest. As two commutators for each of the two stampings would represent a stock of four different types of commutators per machine it will be advisable to arrange the diameter of the commutators so that the same one can be used again in the next larger size machine. This will be easily possible if the brush rocker-gear is arranged mechanically to fit both the smaller and the larger machine.

With regard to the carrying of the current for the lower voltages, it will be advisable to make the commutators of sufficient length for the highest output at 230 volts and to use the same commutator, but with narrower brushes for 500 volts, as explained previously. For special outputs, or lower voltages than 230, and for higher speeds, it might be necessary to make a special commutator, and an allowance of 30 per cent. on the standard lengths should be more than sufficient to carry any of the standard outputs at 100 volts, especially if one uses wider brushes covering a larger number of sections. Provisions for this extra length must be made in the design of the frame, and of the bearing brackets, so that no alteration should be required on the standard shaft.

The fixing of the windings for the different outputs should be done by starting from the best possible average output of the machine, and by systematically trying all possible combinations of coils in the slots, without alteration to the number of commutator bars. The armature coils must, of course, be wound in such a way that the same coil can be connected up in "wave" or "lap" winding, according to the requirements. Taking a 12-H.P. 4-pole motor as an example, and assuming that to obtain a speed 1,000 revs. per minute at 460 volts, a coil of 4 turns per commutator bar should be required, the coils being connected in parallel, the same coils will be used again to give 6 H.P. at 500 revs. per minute, with the coils connected in series, provided always that the heating allows of this output. By connecting up this coil so as to have only half the number of active conductors of double the section, the armature will give 12 H.P. at 1,000 revs. per minute, and again

6 H.P. at 500 revs. per minute for 230 volts, as well as 6 H.P. at 115 volts, all with suitable connections. Taking now another coil with six turns per commutator bar, this will give when connected in series approximately 8 H.P. at 750 revs. per minute at 460 volts, and $3\frac{1}{2}$ H.P. at 375 revs. per minute at 230 volts, as well as 8 H.P. at 750 revs. per minute at 230 volts, with coils in series or parallel as before. Although less latitude is possible with an uneven number of turns per commutator bar, it will be seen at once that with one commutator only a large range of outputs and speeds and voltages is obtainable. The outputs at 500 volts are usually obtained by speeding up the machine by 10 per cent. from the output at 460 volts.

The question of stocking complete armature coils suitable for standard winding is a difficult one to settle, as a stock of this kind has only a limited life. The tape covering after being varnished becomes oxidised and brittle, so that it would be impossible to place the coils in any slot even with the greatest care if the coils have been made many months beforehand. As at the same time a certain amount of stock must be at hand to give quick deliveries it is important to regulate this stock as closely as possible to actual requirements.

When using bar winding, and especially in large machines, a series parallel winding of the armature offers the greatest attractions from a standardising point of view, because it makes the numbers of bars in the commutator practically independent of the flux of the machine. The bad experience made by several designers with this kind of winding has, however, greatly reduced its use, although lately it has been brought forward again in connection with a special system of balancing.

The question of the carbon brushes to be stocked is a trying one, as it is only by having a large variety of carbons that sometimes it is possible to work in a type to give a certain output, and in this direction the high conductivity brushes and those made by the Morgan Crucible Company have done much to help the designer. On the contrary, the brushes with graded resistance also issued by the same company have not met with much success, on account of their unsatisfactory behaviour when heating up, and of the difficulty of not being able to reverse the direction of the machine without changing round all the brushes.

The ventilation of the machines will also have to be considered very carefully, as the modern high ratings are only possible if the losses are carried away continuously by an efficient flow of air. The methods of obtaining this ventilation are really part of the mechanical design and need not be discussed here.

In fixing the winding of 2- or 3-phase machines, a suggestion has been made very often of the possibility of leaving the coils disconnected, so as to obtain a winding suitable for a large number of voltages by grouping together the poles in one or more parallel circuits, also by bringing out both terminals of each phase and connect them up on receipt of the order either in star or mesh. Both suggestions

are correct, but it will be found in practice that they are only suitable for exceptional cases because the stocking of a motor which is not completely wound is not a satisfactory arrangement. The machine has to be returned to the winding department for connecting up on receipt of the order, and is often not in its best condition if it was kept in stock for months with a large number of loose connections hanging from it. The best solution under the circumstances appears to be to wind rotors completely for a given number of poles and stock the motors in all the components without winding the stator. On receipt of an order the machine can be finished in less than a fortnight, and this will be found quite satisfactory in most cases, especially when a small stock of ready wound machines is also kept for all normal voltages.

Discussion at Glasgow, March 8, 1910.

Mr. Barr.

Mr. J. R. Barr: I think it used to be the practice ten or fifteen years ago to design machines for a given rated output and speed with the same armature and field magnet dimensions for all voltages between 125 and 500; but this has been abandoned in the most recent practice. In fact, there should in many ways be a greater difference between a 500- and 125-volt machine for the same output and speed than between two machines of the same voltage and very different outputs. Firms standardising a line of machines of many listed ratings from the smallest sizes up to 100 k.w. or more are, for commercial reasons, reluctant to admit the economy of this principle, and are generally opposed to the designer bringing in these modifications. The crude practice of having the same length of armature core and commutator for 125 and 500 volts is still maintained by some manufacturers. If one examines a low-voltage machine it will often be found that the commutator has much less liberal dimensions than is given to the same size of machine wound for 500 volts. In getting out a line of standard machines there should at least be two lengths of core for each diameter—one length for 250 volts and the other length for 500 volts. Even when this principle is observed a large amount of standardisation is possible, for there is one thing common to all machines of the same output but having very different voltages—namely, the amount of energy to be transformed. Hence it is quite logical that one should endeavour to employ the same bedplate, bearings, shafts, etc., and keep the same overall dimensions for all voltages. The same peripheral speed could be adopted independent of the voltage, and in the case of the commutator this should be as high as possible—say, about 12 or 14 metres per second. Whether the machine be for 500 or 125 volts, a high peripheral speed is an advantage. In a high-voltage machine more space will be available for the commutator segments, so that a greater number can be used, thus keeping down the reactance voltage. With low-voltage machines the radiating surface of the commutator is generally what fixes the overall length, so that if we adopt a large diameter the length will be proportionally diminished. For a given output and speed the same

commutator diameter will hence be suitable for any voltage, and the only dimension that need be different is the lengths of the armature and commutator. The length of armature plus commutator can therefore be kept the same for all voltages, and so give the same centres between bearings. In a low-voltage machine a longer commutator is necessary in order to collect the larger current, whereas the length of the armature can be much less than in a 500-volt machine. There is also no objection to employing for all voltages the same diameter of magnet yoke and length of poles. The variations with rated voltage are hence limited to the widths of magnetic circuit, armature core, and commutator, as well as the windings and number of segments. Since of the variable parts—magnet frame, armature stampings, and spider, commutator spider, and brush-holder supports—the diameter is the same for all voltages, it is practicable, by the exercise of care and ingenuity, to arrange to use the same drawings and substantially the same patterns for machines of any voltage, the patterns being constructed so that they may be extended or shortened as occasions may require. Mr. Barr.

Mr. W. L. Spence: I cannot help taking exception to Mr. Orsettich's description of "rain-proof" motors as "enclosed ventilated"; the latter term I would apply to machines with air-cooling tubes and a fan. The use of the same end shields for both alternating-current and direct-current machines is undesirable, as it renders the interior of the machine particularly inaccessible, and cramps the design of other parts. In my opinion cylindrical end covers are best. Mr. Orsettich did not touch on the question of ball bearings. These should only be used at the commutator or slip-ring end, and not at the pulley end; I do not think that they would give satisfactory results on heavy geared drives. I must say that I disagree entirely with Mr. Orsettich's views on spiders; in my opinion they should be used down to the smallest possible sizes of machines, as they very considerably simplify the process of winding, and entirely obviate the risk of having a well-ground and centred shaft spoiled by being dented by a hammer or otherwise while in the winding shop. I was surprised at the author's opinion that any type of well-made brush-holder was admissible; the rocking-arm type of brush-holder appears to my mind to have many serious defects, and cannot compare with the box type of holder for sparkless running. Mr. Spence.

Mr. C. McMillan: Although Mr. Orsettich has limited himself chiefly to the commercial aspects of the subject, it is almost essential—because of the number of compromises that are required—that we should touch very closely on the two allied subjects of detail, design, and methods of costing; and we can probably not consider the primary subject of the paper without bringing in some notes and comments on these allied subjects. The subject which interests me chiefly in this paper is the general subject of the attempt to obtain standardisation through a better understanding being reached by the various people concerned in manufacturing electrical machinery. The Mr. McMillan.

Mr. McMillan.

point has been raised again and again pretty much in terms such as Mr. Orsettich uses, but I think it could be reduced to a more definite problem. I refer chiefly to the demand by customers for special variations from standard lines of machine that a manufacturer has gone to the trouble of standardising. A buyer or his consulting engineer takes an obstinate stand for exactly the thing that he thinks he wants, and an equally definite stand is taken by the manufacturer who attempts to supply only what is obtained by economical standard methods. The real compromise is to give the customer exactly what he wants, but make him pay for it exactly what it costs, as near as that cost can be discovered. In a highly competitive industry it is from considerations of policy that the manufacturer yields to the demands of the customer, but if it were realised how much he was sacrificing in doing that, he would probably find some other method of propitiating customers. A company might take up a wrong attitude by too firmly opposing a new requirement by a customer, because that one order might be the forerunner of a large productive business in the future. I would suggest that there should be another element in the costing besides the standard cost of the machine, and that the cost of an entirely new development should be charged partly to the customer and partly to some other account registered for the purpose. It might be called an advertising account or an enterprise account, and for the remainder of the extra cost the purchaser might be penalised for demanding a new type of machine. It is rather doubtful to what extent a manufacturer should assent to specific demands of the customer or consulting engineer. The manufacturer is in the most favourable position for knowing the real wants of the market, and he might do a great deal more to educate the customer than is done at present. In every case it should be the aim of the manufacturer to let the customer understand clearly the expense in which he is involving the industry and himself by his special demands.

Discussion at Birmingham, March 9, 1910.

Mr. Railing.

Mr. M. Railing: We are greatly indebted to Mr. Orsettich for his able and remarkably clear paper. The subject is not new, and we are all aiming at it and wanting it, but we need to remember that we have to consider in this connection commercial, mechanical, and electrical interests. These subdivisions will greatly help to an understanding of the subject. From the manufacturers' and the commercial point of view we all agree with standardisation, because it protects the manufacturer and enables him to produce much more cheaply in large quantities than in turning out small special quantities of machines. A small order involves exactly the same routine work as a large one. One machine is as troublesome as a hundred, and perhaps requires even more special attention. As manufacturers, therefore, we welcome standardisation, because it also fully employs the machines and tools, gives a regular flow of employment to the workmen, and reduces the

Mr. Railing.

cost of production. Equally from the designing point of view it is much more satisfactory if we can turn out a large number of one kind, and it is better to concentrate over component parts than worry over one machine. The designer can then make the best use of his knowledge and material. From the public point of view it is still more important. It aids cheap production by saving capital expenditure, and it is all-important that production should concentrate upon proved types and not experimental types. In case of breakdowns, which will happen, it is very important to be able to draw upon existing stocks, and that means increased facilities to the consumer. It is very necessary that manufacturers should combine with consumers, but especially among themselves, to make as much use as possible of the rules laid down by the Institution. But I fear that in actual practice it does not work out in that way. It is very rarely that consulting engineers adhere to the rules which the Institution has laid down. If the rules of the Institution do not cover the whole ground, by all means let us put our heads together and try to enlarge them. But I am convinced that only by the co-operation of the consumer, his advisory consulting engineer, and the manufacturer can we arrive at standardisation. In this respect our friends on the Continent are very much ahead of this country. But there is no reason why if we agree tenders should not be offered on the basis of the Institution rules. The question of standardisation is a wide one, and even of national importance. As Chairman I do not want to touch upon the fiscal question. But it is a fact that those of us who have to compete against large outputs of well-designed machines coming from the Continent and the United States can only hope to hold our own by standardising as much as possible. In this respect we must work together as much as possible.

Mr. Smith.

Mr. S. P. SMITH: There are many points in connection with the standardisation of machines that appeal to the designer. One important point he has to consider is the question of labour *versus* material and to decide where he should economise. This is rather an important question, especially for the workmen. But the only satisfactory solution from the designer's point of view is to study the works cost of the machine. In general, it is found in electrical machinery that material is a much more expensive item than labour, though it varies considerably for different kinds of work. In an induction motor, for example, the labour will be more costly for high tension than low tension. It will generally be found, however, that labour is of minor importance compared with material, so that in the long run the designer will do well to cut his material as far as possible and improve his machine by securing good workmanship. An illustration may be cited in connection with the question of the insulation of slots. If only a small amount has to be paid for winding the armature it is clear we cannot expect the same quality of workmanship as if a higher price were paid. But if a somewhat higher price is paid the work will be done more carefully and the designer will be able to use a finer insulation, and the effect will be that in the end the output of the machine will be

Mr. Smith. increased. In the designing of the machine the question of labour *versus* material will be found always to arise. Another important point relates to the quality of the material. On the whole it will be found that the best material is the cheapest, and the extra cost paid for it will be amply repaid by the increased output for a given weight. Success also depends very much upon what might be called "sound finance." Though it is not stated in so many words, it is very evident that if we read between the lines of the paper Mr. Orsettich has a very clear conception of finance by the methods he proposed. For example, a remarkable thing in the design of machines is that we can get two different machines both apparently satisfactory as regards guarantees, and yet one will be 10 to 20 per cent. cheaper than the other. These are very important points from the commercial side and are equally interesting to the designer. We must therefore have a commercial interest in a machine as well as a scientific interest. Another most important feature affecting standardisation relates to the ventilation and insulation of machines. Probably we know about as much regarding the active materials as it is possible to know, but the question of ventilation and insulation is by no means final. It could be accepted almost as an axiom that provided we can improve the ventilation we can increase the output in proportion. Most of the modern designs are certainly based on that aspect of the question. With regard to insulation, although the idea may seem strange, yet I do not see why the allowable temperature rise of the machines should not be much higher if we can find better kinds of insulating materials. As is well known, a gas engine or a steam engine works at very high temperatures inside the cylinder. Hence, if we can really get a reliable insulating material, such as asbestos, combined with a good insulating property, I do not see why, instead of drawing the line at 70°, we might not have a rise at 170° or even higher, provided we keep well within the fusion-point of copper. I believe we should find that it is possible to raise the limit very considerably, and in the long run the customer would be the gainer. He would have a cheaper and lighter machine, and though it would be a hotter one, yet with a material capable of withstanding the heat the life of the machine would not be much shorter. It is quite true, however, that this insulating material has yet to come. A further question arose with respect to what machines ought to be adopted as standard. Take the case of induction motors. If we get a high-speed motor we can design machines combining minimum cost with the best guarantees for power factor and efficiency. But when we come to low-speed induction motors we find those two things opposing one another, and if we try to make a cheap machine down goes our power factor, and the question is where to draw the line. It has to be decided, therefore, whether a cheaper machine with a lower guarantee should be given or whether more should be paid for the machines and a higher guarantee demanded. In the case of continuous-current machines it is often a very difficult thing to know what speeds to design machines for. One is inclined

sometimes to wish that our speeds were also governed by some such factor as frequency, so that it would be possible to define the speeds. At present we have not got that limitation, and so we have to be willing to supply whatever speed is required. Probably the most practical way of settling the speeds is to arrange them in some kind of geometrical progression, so that the jumps would get larger as the speed increased. There is a great amount of variety between different makers. Sometimes the ratio is 1·2 to 1·3, and we can easily find suitable speeds, which can be then listed and brought into line with the different windings, and so on. It is the same with regard to output, which also seems naturally to follow a geometrical progression. Thus with a ratio of 2 we should have motors of 2, 4, 8, 16, and 32 H.P. An arithmetical progression would not be of much use for the market. The only other point I wish to deal with is with regard to specifications. I do not suppose my own personal view will be a very acceptable one, and it may be said that I am not speaking altogether disinterestedly. But I am strongly of opinion that much in the specification is unnecessary from the customer's point of view. Of course, there are always certain points which have to be insisted upon, but the ordinary guarantees might generally be left to the manufacturer. This may be found strange, but there is always the safeguard of competition. Moreover, if the buyer cannot get what he wants from one maker he can always get his requirements from another, while the consulting engineer would be there to see that the guarantees were properly fulfilled. Many of the specifications, of course, are perfectly reasonable, but quite a number of them merely embody whims and fancies to which the English people are very susceptible. I am rather inclined to favour the Chinese point of view and insist that the manufacturer should furnish his own specifications and be made to work to them rather than work to those of the customer. Personally, I would prefer to work under these conditions, for not only would it give the customer a cheaper machine, but, taken all round, I believe it would be a better one. Mr. Smith.

Mr. N. B. Rosher: The speaker has shown considerable restraint in not complaining of the great number of types of machines which have to be made nowadays. In my opinion the number is unnecessarily large. I have had the curiosity to examine the list of electrical undertakings published by the *Electrician*, and it is astonishing to find how the frequencies vary. Taking one page at random there were five alternating-current stations, and they had four different frequencies; that seems rather a large variety. On a further cursory glance through the remaining pages of the list, I found that there were at least 16 frequencies in use at the present time. With regard to the position of the slip-rings I agree with the author that for alternating-current motors the best position is outside the bearing bracket; a slight disadvantage is that should it be required to take out the rotor it would be necessary to remove the rings unless the bearings were split. The material of which slip-rings should be made is by no means standardised. In some cases they Mr. Rosher.

Mr. Rosher. are made either of gun-metal or phosphor bronze, but many firms use cast iron and in some cases cast copper or hard-drawn copper. The same thing applies to brushes which are constructed of copper gauze or carbon or some special mixture of carbon and metal. With regard to ball bearings, many people are finding that ball bearings are not all that they thought they were going to be for large-size motors, although they have proved quite satisfactory for motors of small size. I would like the author's views on this matter. Another detail difficult to standardise is the arrangement of terminals. I prefer a cast terminal box which can be screwed to a flat face on either side of the machine. Where the wiring is carried in steel conduit, I have found, by experience, that the best method to adopt is to insert a 4 or 5 ft. length of flexible metallic tubing between the terminal box on the motor and the steel conduit. This arrangement allows for the movement of the motor on its slide rails and also ensures metallic connection between the motor frame and the conduit system, while at the same time it protects the cables from injury. Mr. Smith has spoken of 170° F. as a desirable limit of temperature rise, but motors having a temperature rise of approximately this order are being regularly supplied for work to one of the Government departments.

Mr. Gott. Mr. A. E. Gott: The subject of standardisation is one of the most interesting ever brought before us, its object being to produce the maximum value at the minimum cost. The author lays stress on the importance of stocking for orders. We should all like to do this, but it is only possible when everything is standardised. It is surprising the amount of money that is spent, and sometimes wasted, remedying small defects which greater standardisation would have prevented. In the examples mentioned, I cannot help thinking that 1,000 and 2,000 revs. per minute, as speeds for 100 and 1 H.P. machines respectively, are much too high. Does the author propose that these speeds should be standardised? In my opinion electric motors generally are run at speeds too high for good application. With regard to voltage we cannot have standard designs without standard voltages. I have been struck with the extraordinary number of different voltages in use in this country and on the Continent. I have even heard of a declared voltage of 416. In regard to the number of slots in alternating-current machines, an important point to be kept in mind in standardisation is that prime numbers over 50 should be carefully avoided on account of expense in making tools. It is much easier to make commutators of different numbers of bars than to make armature discs with awkward numbers of slots. Nothing has been said in the paper about split frames and bearings, which are absolutely necessary in certain cases of large motors. I have known instances where, in order to get at the armature, it was necessary to elevate field, armature, and bearings bodily several feet, whereas this would not have been necessary if the bearings had been split. With regard to reduction gearing, I entirely disagree with

Mr. Gott.

the practice of putting the gear on the top of the motor. It is not only the worst place from the point of view of safety, but the frame is never designed to stand the strain, and it is consequently liable to get broken. I think that in standardisation allowance ought to be made for the fitting of flywheels to the motor shafts, as there are a great many applications where a flywheel not only improves the driving, but enables us to use a smaller size of motor. In many cases discrepancies have been found between power estimates and actual requirements, and failure is frequently due to the want of a flywheel. In regard to small parts many manufacturers do not pay enough attention to details, the terminals especially being frequently neglected by the designer. We sometimes see them fastened on to the bedplate or even the foundations because they have been left out entirely from the design of the machine. Terminals ought to be arranged so that the assemblers could connect coils in such a way that the minimum amount of labour would be required. This facilitates final testing and coupling to secure desired polarity and rotation. I would suggest that the best arrangement of the terminal blocks is one in which the ends of the armature, and both the shunt and series coils, are brought to separate terminals. The centres of certain of the terminals are equidistant, but the arrangement gives increased distance between the two ends of the shunt. Workmen can be relied upon to join the separate bobbins of shunt or series coils up to each other correctly, but the final connecting of series, shunt, and armature to each other is a test-room matter. In the arrangement I suggest the ends of the coils are connected by the workmen to the terminals irrespective of polarity, and it is the duty of the test-room to interconnect the terminals by means of links to secure the desired polarity and rotation. The arrangement satisfies every condition of service.

Mr. Anderson.

Mr. A. C. ANDERSON: At the bottom of page 132 there is a paragraph referring to the reduction of profit and the increased cost of the commercial department, which says, "The percentage of the price required to cover these two items has remained practically the same." Are we to take the percentage represented by profit on the total price as being the same as it used to be? Again, on page 133 there is a paragraph which says, "The benefit of keeping one's workmen constantly employed on the same line of work shows itself in the increased skill they acquire in the performance of the operation or in the handling of a given machine." But there is some danger that by keeping men on the same line of work we shall make the man a machine. The same thing applies to the standardisation of designs. It is a very fair question to ask whether that does not tend to the stultifying of invention. It might be said that we can apply our ingenuity to further standardisation all the time, but it is a great point as to whether everybody would conform to the same line. It seems a fair argument that, with three or four different varieties of work, the manufacturer and the workman will reach a much

Mr. Anderson.

higher point of efficiency and economy of material. On page 135 there is a paragraph about the flexibility of type which seems to me to be a very important point indeed. Most of us have met non-technical men who, after reading about electrical machines, described as having 95 per cent. efficiency, wonder why they do not get that efficiency with a 1-H.P. motor. On page 139 it is said that "for continuous-current machines, where the types of the frame and the number of poles are settled beforehand, it is always advisable to have a separate diameter for each length unless the manufacture is very small indeed." Personally I do not agree with that. I think we ought to have at least two lengths to get the requisite degree of flexibility, because it is a very difficult matter to standardise armature windings. The same remark applies to page 148, where it is said, "The stampings of the continuous-current machines should be arranged for one or, at the maximum, two numbers of slots only." But suppose we have one diameter and one length with two numbers of slots, we shall have a very expensive and a very numerous line of dies and patterns. I would like to refer also to page 144, where it is said, "It will therefore be advisable, in order not to obtain machines which are too light for large outputs, to increase the flux per pole at the same time as the number of poles. In this connection I would rather like to know exactly what effect the increase of the magnetic leakage has on the producing power of the machines from the point of view of the field copper, and especially with regard to interpole designs.

Mr. Willmott.

Mr. A. WILLMOTT: Speaking from the point of view of the shop manager, it appears to me that the paper has rather missed the initial start of standardisation. Every shop manager knows that what he wants to start with is correct shop drawings. There is, however, very little said about drawings in the paper. One of the speakers said that the paper was most excellent with regard to shop organisation, and I agree that it should prove a help to standardising production. There are, however, two points left out, viz., Inspection and Test. No mention is made of inspection, and that is a very important point in regard to standardisation and shop production. If we do not want to waste money we must have good men who can be relied on to see that when machines are going through the shop there shall not occur trivial defects which will be discovered afterwards on testing, and so cause delay. Taking machines back to be rectified is one of the things which runs up works costs. On page 140 the paper mentions only cast iron for the frame of the yokes. I think we have got a little beyond cast iron for yokes; we can now get a good quality of steel castings, which designers are using every day more and more than they used to do. The cost was formerly a drawback, but these castings can now be got at fair competitive prices. The author also mentions iron as being used for the sake of quick delivery, but with standardisation we are able to have steel castings in stock. It is suggested in the paper that the brush-holders should be made suitable for such different thicknesses of carbon blocks as might be required to suit the different

amperages. I think the preferable way is not to have various thicknesses, but to increase the number of blocks, and so keep a less number of sizes. One great help to standardisation would be a correct code system for standard parts in the drawing office and works. If the designer and the shop could agree upon a systematic way of placing the parts, a great saving in shop costs can be made. This has been proved a decided advantage in cases where each detail has a reference or distinguishing code number. Mr Willmott.

Mr. W. Holt: One point with regard to standardisation which requires emphasising is the possibility of stultifying progress, and I think that one of the reasons why standardisation has not been carried out in electrical machines to the extent to which it has been, say, in the case of bicycles, typewriters, sewing machines, etc., is that the electrical machine, so far, has not reached finality. But the electrical machine of to-day, as compared with that of even two or three years ago, is a very different article. It has now become almost as perfect as it can be, and the time for considering the question of standardisation has come. But we must first have standard requirements, and in this matter our Institution must play a large and important part. It would be well to be fairly conservative on account of varying requirements which would not justify a special design. With regard to field coils, one winding only should be required for, say, 220 to 230 volts, and where standardised, for 220 volts, allowance must be made for a fair variation. I have known a corporation voltage of 220 rise to 236 volts at certain times of the day. As the copper losses increase as the square of the voltage, a too rigid rating would cause overheating and a breakdown. Also, in the case of alternating-current induction motors, if the cables are not up to their full capacity, and there is any drop in terminal voltage, a heavier current than normal will be required, again causing overheating with a too rigid rating. It must also be borne in mind that an intermittently rated motor may have a rating double the normal, and even then be subject to a 50 per cent. overload, so that the mechanical details must allow for this. On the other hand, this question of conservatism may be overdone, and it is doubtful whether it is advisable to allow for too many eventualities in a standard design. If we have designs which represent so many reservations, the cost of the complete article will be too high to enable it to compete in the open market. It seems to be best to design standard machines for ordinary standard requirements, and to treat any departure from that standard as a special machine. With regard to patterns, I find that they are liable to depreciate very rapidly, and the designs should necessitate as low an outlay in this respect as possible. Accountants allow for a life of four or five years in a pattern, but my experience is that in some cases it is less than four or five weeks before the pattern has to go back to the pattern shop, this being more often the case when castings are purchased from outside. Of course iron patterns can be made, but they are only suitable for very small patterns, as in large sizes they become Mr. Holt.

Mr. Holt. cumbersome. When armature stampings are mounted on spiders, the utilisation of scrap requires consideration. By careful designing the internal diameter of a large stamping can be arranged to be the external diameter of a smaller stamping, and a range of machines up to 28 in. diameter can be designed with complete use of the whole of the material. As regards the question of enamelled wire, I have tried this both with armatures and field coils, and with the latter have had no trouble. For armatures, however, it has been an entire failure, but I put this down to mechanical rather than to electrical difficulties. In the case of very small hand-wound armatures, for 220 volts, there is a general leakage equal to the full-load current of the machine when running empty. With larger sizes and coil windings the trouble seems chiefly due to the handling necessary to place the coils in the slots. Very little pressure or tapping with the mallet where wires cross each other is sufficient to cause short circuits. Speaking generally, any winding arranged in regular layers can be made satisfactory with enamelled wires, but where they have to be twisted and turned, or laid over each other, they are not likely to be satisfactory. I have noticed that in Admiralty specifications the use of enamelled wire is prohibited. With regard to ball bearings, I was responsible some years ago for the mechanical design of a motor-generator combined on one shaft with two single-row bearings. The total weight of the rotor was 20,000 lbs., and the speed 500 revs. per minute. Except for a cracked ball in the first few weeks, I believe the machine has run for three or four years without trouble. I have had personal experience of motors up to 20 H.P. which have run for some years perfectly satisfactorily, and I think that in a great many cases the failure of ball bearings is due to faulty mounting.

Mr. Orsettich. Mr. R. ORSETTICH (*in reply*): Dealing with Mr. Barr's argument that machines should be designed with a different frame according to the voltage, so as to use a heavier flux for high-voltage machines and a lighter flux for low-voltage ones, I wish to say that this is entirely impracticable from the manufacturers' point of view. This suggestion, I believe, was put forward some six years ago by Mr. Hobart, and was actually tried by one firm, but was very soon given up. The reason is that the extra outlay in patterns and stock makes the advantage resulting from the increased output on the low-voltage machines very problematical, whilst it handicaps delivery to an enormous extent. The manufacturers, therefore, prefer rating the types as low as the limit of the high voltage requires it, and sell for a lower voltage a machine which actually can give a higher output, but in every instance exactly the same frame, armature, and mostly commutator, is supplied irrespective of the voltage. Another point which I believe will be found impracticable is the adoption of the high peripheral speed of the commutator mentioned, viz., 12 to 14 metres per second. In an average machine of, say, 10 to 14 in. diameter, the peripheral speed of the commutator, even when running at a fairly high speed of 1,500 revs. per minute, will not exceed 11 metres

Mr. Orsettich.

per second. The adoption of a large diameter commutator will not enable the output of the machine to be increased when working with low voltage, as Mr. Barr seems to think, unless the number of poles is increased in inverse ratio to the voltage, and this, of course, will not be the case if the same frame is used. The large diameter of the commutator would therefore have only the effect of increasing the cost of the machine without any advantage, and at the same time would make the commutation worse by increasing the reactance voltage.

The objections raised by Mr. Spence against the use of the same shield for both ends of a continuous-current machine seems to be based on a misunderstanding. It is not proposed to cramp in any way the design by the adoption of the two shields of the same pattern; on the contrary, the space above the commutator is increased to the same diameter as the frame of the machine, and if the accessibility to the commutator obtained through the openings in the end shields is not satisfactory there is no objection to having additional peripheral openings in the portion of the frame above the commutator. The design in this way becomes one of the cylindrical pattern which Mr. Spence agrees is quite satisfactory. I agree up to a certain extent with his views on the question of spiders, but from the manufacturing point of view there is no doubt that the spider means complication and additional expense. Regarding the type of brush-holders, the statement that both the arm type and the box type are satisfactory is borne out by the fact that some makers have adopted one pattern as standard and other makers the other, and both are able to produce satisfactory machines. The same opinion seems to be shared by the different consulting engineers, and it is therefore necessary for a large company to manufacture both patterns and supply them according to customers' wishes.

Mr. McMillan raised a very important question which affects the policy of every manufacturer. Personally I should not think it advisable for a concern to take a firm stand towards customers' wishes and refuse to yield in any detail. A compromise, therefore, has to be arrived at between the customers' requirements and the interests of the company, and only if the company has some real and plausible reasons for refusing to carry out the customers' request because it might affect the results expected from the machine, is the entirely negative attitude justifiable

In reply to Mr. Smith, it seems to me, that as the matter is put by him it will be rather difficult to obtain alterations of their standard specifications from consulting engineers. I take it that what is really meant by Mr. Smith is that the specifications of the consulting engineers should be first of all for the purpose of laying down the principal lines of the schemes, and should state clearly their requirements, but should not be for the purpose of insisting on small details of construction which could be executed in several equally satisfactory ways. The specification further should lay down clearly all

Mr. Orsettich.

the points which are of importance for the satisfactory operation of the plant, points which would have to be verified by a test before the plant could be accepted. If this is the meaning of Mr. Smith's remarks we are perfectly in agreement, and I believe that every consulting engineer will be of the same opinion.

With regard to Mr. Rosher's remarks concerning the large number of machines proposed as a basis of standardisation, this is an essential condition of its acceptance and success. If the number of machines of a standard line is not sufficiently large to cover all requirements, there would be occasion for special machines to be made, and this is the very point to be avoided. Dealing with the question of slip-rings, I think the advantage of being able to inspect the rings continually during the running of the machine should weigh more with the user than the difficulty of having to remove the slip-rings whenever the bearing bush has to be renewed. This, however, affects only small machines, because in all large machines the bearings are split, and it is then perfectly easy to remove the bushes without affecting the slip-rings. The material used for the slip-rings is not of great importance, especially where short-circuiting gear is fitted to the motor. Phosphor bronze, steel, and malleable iron have all been employed. If the rings are shrunk on to an insulating bush, I think malleable iron is more satisfactory than steel or phosphor bronze. Bronze has the advantage of not becoming rusty if left standing for a long time, but it is more expensive and less durable. With regard to the material for the brushes in standard machines, this should be carbon only, but in exceptional cases whenever very low voltages and heavy currents have to be dealt with, it is permissible to use carbon of special composition, containing a certain amount of copper or other metal which will increase the conductivity. These carbons, however, besides being fairly expensive, have all the disadvantage of causing a more rapid wear of the commutator surface than ordinary plain carbon. In addition, they often alter their conductivity entirely under the influence of heat, and are therefore not very reliable. Copper brushes are permissible with slip-rings, especially if they are made of malleable iron, and also in cases where the brushes are lifted off the slip-rings as soon as these are short-circuited. In connection with ball bearings, these have two very great drawbacks. The first one is that it is extremely difficult to fix the ball-races to the shaft. A tight fit is recommended by the makers, because otherwise the race is likely to run round the shaft. If, however, the ball-race is forced on the shaft slightly too tight, the race expands sufficiently to lock the balls in the outer race, or else it cracks. Ball-races with conical seating are in this respect much better than ones with plain cylindrical seating. The second drawback is that it is impossible to prevent some of the balls from breaking, and that whenever a breakage takes place parts of the broken ball wedge themselves in between the two races and lock them. The result is that the inner race, which is hardened, cuts the shaft very badly, so that it is necessary to renew the shaft as well as the ball

bearing. Roller bearings are being developed at the present moment by the makers, and I have no doubt that if these can be obtained at a reasonable price they will be much more successful than the ball bearings. With regard to terminals, if it should be possible to come to agreement as to their position, manufacturers will be very glad to comply with any requirements. Mr. Orsettich.

I agree with Mr. Gott that the speed of machines should be kept as low as possible, but it is a fact that there is a big market for high-speed machines at the present moment, and manufacturers have to include them in their lists. With regard to standardisation of voltage, a slight difference of 15 or 20 volts between different supply companies does not affect the manufacturer, as the same armatures can be used in both cases, and if the difference is small, even the same field winding. The speed of the machine will be slightly different, but this can be taken into account when offering the machine. With regard to splitting the frame of the machine, the general practice is to do so whenever the armature becomes too heavy to be lifted out by two men. This is the case for all armatures above 14 or 15 in. diameter.

Replying to Mr. Anderson, I am not afraid that the adoption of strict standards will lead to the crystallisation of types and stoppage of progress. Apart from the fact that every manufacturer is continually trying to improve his own types, there is the fact that competitors do not start producing the machines all at the same time, so that whenever a new type is put on the market, firms manufacturing older types are bound to bring out improvements to be able to hold their own.

I agree with the remarks of Mr. Willmott that the question of drawings should be thoroughly discussed in connection with standardisation, but I would refer him to my remarks in the beginning, stating that the paper did not deal with the question of standardisation from the shop point of view, and that therefore this point, as well as the question of inspection of parts, should be omitted. I am afraid that the suggestion of altering the number of brushes instead of their thickness is hardly practicable, because it means increasing the length of the commutator every time the current of the machine is increased. The adoption of steel for the yokes of machines *versus* cast iron is a difficult matter to settle. From the designer's point of view, steel is preferable in most cases, as it enables a slight amount of copper to be saved, but from the general manufacturing point of view it is very troublesome, as steel castings require a long delivery, which is equivalent to necessitating a large stock being kept. Again, it would make the delivery of special types extremely long.

In reply to Mr. Holt's statement that often a slight increase of the current above the standard would make the machine too hot, I would say that it is entirely a matter of fixing the limits of the standard sufficiently low to allow plenty of flexibility in all directions. The object of standardisation is to cheapen production through manufacturing the machines under favourable circumstances, and not by cutting down the design to certain definite figures of voltage and speed. As

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regards using armature stampings obtained from the centre portion of a large machine for smaller types, my experience is that this is worth while doing whenever the diameter of the spider of the large machine is 10 in. or more, but if smaller pieces only can be obtained the cost of making the spider for the large machine is more than the saving obtained.

I agree with the remarks as to the use of enamelled wire. This wire can be used in most cases for the field winding, but it is entirely unsuitable for armatures. The reason is that the makers at the present moment are not yet in a position to guarantee that the wire is covered evenly the whole length, and that it is a common occurrence to discover bare pieces of an inch or two in length ; and whilst these do not matter seriously if wound in a shunt coil, they will cause certain breakdown if used on an armature.

THE PHYSICAL PROPERTIES OF SWITCH AND TRANSFORMER OILS.

By W. POLLARD DIGBY, Associate Member, and D. B. MELLIS.

(*Paper received from the* MANCHESTER LOCAL SECTION, *February* 12, *and read at Manchester on March* 22, 1910.)

INTRODUCTORY.

In presenting to a gathering of electrical engineers the present paper upon switch and transformer oils the authors must at the outset disclaim any broad claim as to absolute originality in its contents. The bulk of the contents of this paper represents the fruit of investigations extending over many months, which were initially undertaken without any ideas as to publication, but for the sole purpose of acquiring knowledge as to the electrical properties of these oils in general, and the respective merits of well-known brands in common use. The subject is one whose bibliography has not formed the subject of a comprehensive review in this country since the paper read before the Institution by Hughes in 1892 on "Oil as an Insulator." Yet in other branches of engineering science the study of materials which has commenced with the examination of physical properties before use has since tended towards examination of their properties and deterioration during use. Oil for oil-break switches and transformers has certainly not received the preliminary attention in the laboratory, nor the investigation in use that has been given to, say, transformer iron or to steel rails. As a result of casual rather than scientific selection, followed by carelessness and neglect, much trouble has probably arisen. Generally, the electrical engineer has purchased his oil on the strength of the literature of one or other of the rival makers which has guaranteed a flash-point, specific gravity, viscosity, and degree of chemical purity, or else upon a curve of the dielectric strength of a special sample of the oil. Thanks to taking matters on trust in this manner, the purchaser has not been aware that while flash-point, specific gravity, and viscosity are generally as advertised, the guaranteed chemical properties are less frequently afforded, while the widely circulated splendid curve of the dielectric strength (which was true enough of the special sample) is rarely reproduced on any commercial sample. Otherwise the electrical engineer has specified flash-

point, viscosity, chemical purity, and dielectric strength over a defined gap, and tests taken of one or two samples selected at random have been made. Unfortunately the contents of the several drums forming a simultaneous consignment of oils vary so greatly in their chemical purity, and still more in their dielectric strength, that tests of random samples are sadly misleading. Moreover, while the ohmic resistance of the copper used in all our operations is the subject of precise definition, and while minute impurities would indicate their presence by increasing the resistance, say, of a copper cable, the electrical engineer has not yet thought it worth while to investigate, and still less to specify, the specific resistance of this fluid insulating material. The omission of this means of testing has precluded the prompt discovery of minute traces of foreign matter which largely affect insulation resistance, although P. Humann, in 1903,* urged that the property of a high insulation resistance was desirable.

It is therefore with the object of urging the systematic examination of oil before use, as well as suggesting standardised methods of testing, that the authors now put forward their account of some of the investigations which they have undertaken of some of the physical and chemical changes occurring through use. In so doing they desire to deprecate such criticism as that any good book on oils describes a viscosimeter or an apparatus for determining flash-points, or that others have discussed the relation between methods of taking dielectric tests of oil. While they consider that even the makers of the best oils fail every day to maintain a standard quality of excellence, they consider the electrical engineer to be equally to blame for not having insisted on uniformity of quality. For obvious reasons no single brand of oil is referred to under its trade name in this paper, but all samples are distinguished by initial letters and numbers.

Regarding oil as an insulator, it is an obvious deduction from the physical facts of electrical conduction through metals and alloys that, just as the presence of any impurity in a metal increases its specific resistance, so the presence of any soluble impurity in oil must tend to decrease its value as a medium offering a resistance to the flow of electric current. The parallel case of another fluid—viz., distilled water—has close points of resemblance to oil used as an insulator. Distilled water when exceptionally pure has a specific resistance of 700,000 ohms per cubic centimetre, and normal good distilled water a specific resistance of 300,000 ohms. The addition to a litre of the last mentioned of only 1 milligramme of sodium chloride suffices to reduce the specific resistance to approximately one-half. The grading of oils according to their specific resistance gives a fair indication of their purity. There is, however, a large range in the specific resistance depending on the presence or absence of impurities in an amount determinable qualitatively as "traces" rather than quantitatively as analytically ascertainable volumes.

Impurities ordinarily present in the oils supplied for use for

* *Elektrotechnische Zeitschrift*, vol. 24, pp. 760 and 875, 1903.

oil-break switchgear or for transformers fall under the following heads :—

1. Moisture.
2. Alkaline substances.
3. Resinous or resinoid matter.
4. Acids.
5. Sulphur compounds.

Their presence may be due to improper or inadequate refining, or to wilful adulteration, or to accidental contamination.

In storage the oil may undergo certain chemical change. An alkaline oil would be likely to absorb moisture from the atmosphere, which would lower both its dielectric strength and its specific resistance. An oil stored or transported in wooden barrels might be contaminated by resinoid substances.

During use in oil-break switchgear chemical and physical changes occur. These include the absorption of moisture from the atmosphere, the carbonisation of the oil, increases in specific gravity and in viscosity and changes in flash-point. Also dust finds its way into the oil tank, while the effect of the arc which is broken on opening the switch is to produce decomposition and a gradual change in the properties of the oil. When used in transformers the absorption of vegetable oils from varnishes, nominally but not actually oil resisting, is probably the most prolific of the sources of trouble. Dust, in this instance, also finds its way into the oil, and either or both of these foreign matters will render the oil more viscous, and restrict or reduce its circulation; further, through electrostatic attraction, dust adheres to windings and core, interfering with the heat transfer in much the same manner that scale limits the transmission of heat through boiler plates.

Of the properties requisite in a mineral oil for transformers the authors would urge :—

1. Absence of moisture.
2. Good dielectric strength.
3. A low viscosity to facilitate the heat transfer from the core and windings to the case.
4. A flash-point expressed by a figure which is two to three times the designed temperature limit of the transformers in °C.
5. An absolutely neutral reaction.
6. Complete absence of vegetable oils or resinoid material.
7. Freedom from metallic salts.

For switchgear the authors would emphasise the need of points 1, 2, 5, 6, and 7. Viscosity is discussed later in the paper, and the flash-point might be put at least six times the expected engine-room temperature.

The following preliminary notes are collected from the laboratory

records of one of the authors upon a number of oils passing through his hands before their joining forces to study this matter :—

P 1 was a switch oil having a flash-point of 173·5° C., and a viscosity of 94·4. The specific resistance was only 149,000 megohms per cubic centimetre. This oil was rejected without further examination.

P 7, also a switch oil, was found to have a specific resistance of only 2,127 megohms, and to have a heavily alkaline reaction. Its dielectric strength was found to be 4,000 volts between ½ in. diameter balls 100 mils apart.

P 8, from the same maker, was rejected for alkalinity and resinoid matter, the specific resistance being 46,800 megohms.

P 9, also from the same source, had a specific resistance of 683,500 megohms, and was approved as an official sample.

P 14 was the oil supplied, and nominally in strict accordance with P 9. Yet its specific resistance was only 262,000 megohms, and it was found to be slightly alkaline and to contain considerable resin. On a dielectric test, it was found to break down at 6,230 volts between brass balls ½ in. diameter and 100 mils apart.

P 10 was a transformer oil stored in a wooden barrel. Its specific resistance was found to be 382 650 megohms, with slight traces of resin, and 0·57 per cent. loss at 100° C.

P 13, offered in substitution for P 10, had a neutral reaction, was free from resin, and had a specific resistance of 2,088,600 megohms. It had been stored in a steel drum.

P 15 was a switch oil with a distinctly alkaline reaction, and showing 0·21 per cent. loss at 100° C., the specific resistance being 273,800 megohms.

P 19 was offered for use for some transformers. It contained considerable resin, and was slightly alkaline, the specific resistance was 40,000 megohms. Over a distance of 200 mils the disruptive strength of this oil was found to vary from 8,000 to 30,000 volts.

A discussion of the extreme variations recorded above determined the authors to investigate these insulating materials in a systematic manner.

Determination of Specific Resistance.

For the measurement of specific resistance the authors have mainly employed the horizontal form of test-plates with areas of 100 or 200 sq. cm., illustrated in Fig. 1. The apparatus employed consists primarily of two metal discs of even surface arranged parallel to but insulated from one another. The distance between these is regulated by a micrometer head on the spindle of the instrument. This spindle is hollow and of an insulating material such as ebonite. Through the spindle is carried the lead of the bottom plate, a separate connection

FIG. 1.

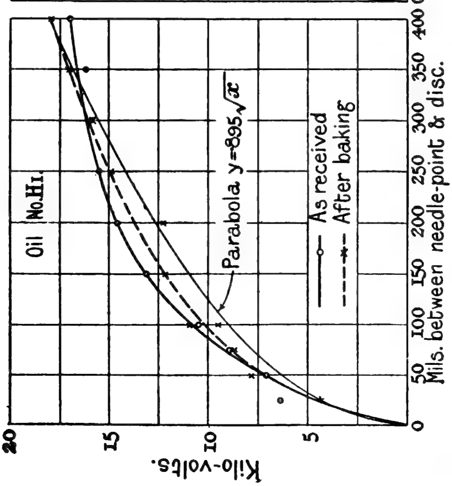

FIG. 2.

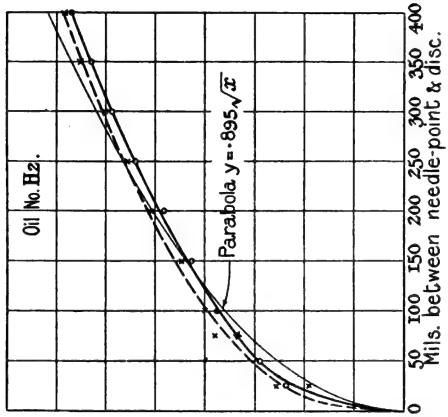

FIG. 3.

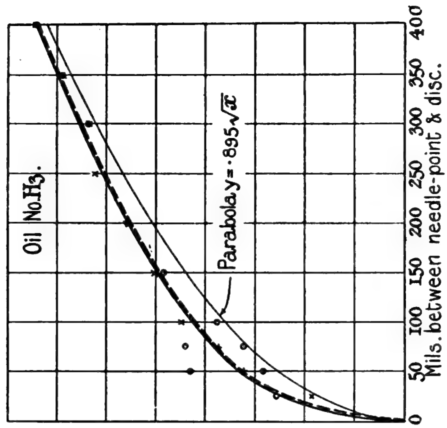

FIG. 4.

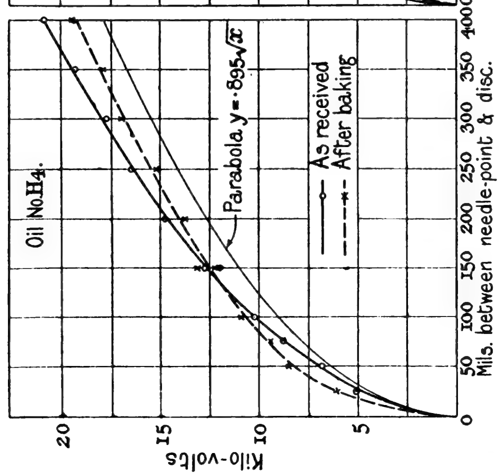

FIG. 5.

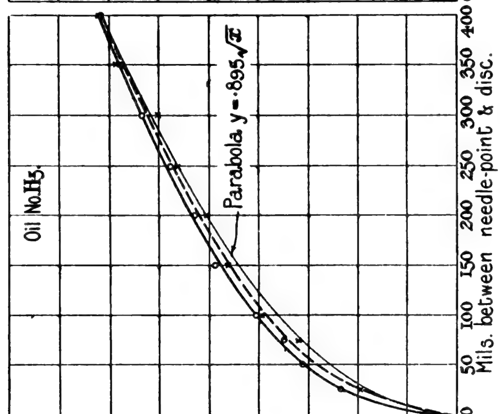

FIG. 6.

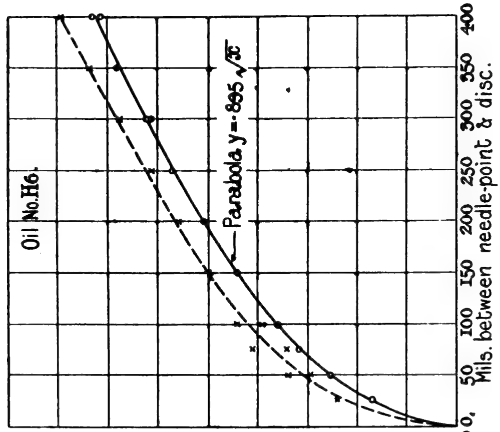

FIG. 7.

being led to the top plate. These leads are connected to a megger or other form of ohmmeter. The handle operating the generator of the megger is then turned, and simultaneously the distance between the test-plates is adjusted by the micrometer head until a steady and exact position is indicated upon the megger scale, taking preferably a point about three-quarters of the distance along the scale. Succeeding readings are taken reducing the distance between the test-plates and the resulting lower megger readings noted. By reason of the fact that a series of such readings, if plotted, gives a curve of hyperbolic shape instead of a straight line (this resembling a curve showing the relation between pressure and distance upon dielectric tests of such oil), the mean specific resistance is calculated as the mean of a series of such readings. Directly the megger needle oscillates violently, or directly sparking takes place, the series of readings is discontinued. The readings must always be taken in a descending order of values for insulation and of film thickness, as when once sparking takes place the specific resistance of the liquid is altered and lower values result. The specific resistance per cubic centimetre for any given distance then equals—

$$\frac{\text{observed resistance} \times \text{area of plates in square centimetres} \times 393{\cdot}7}{\text{distance between plates in mils}}.$$

Properties of Typical Oils.

A series of six special samples of oil, each from a separate maker, was obtained for comparative examination. Dielectric tests between a needle-point and disc were first taken over a series of distances between 25 and 400 mils. The appended set of curves numbered, Fig. 2 to Fig. 7, illustrates the behaviour on dielectric test of these oils in their condition as received from the manufacturer. The apparatus used is illustrated in Fig. 8.

The table on page 172 sets out their physical properties as received.

The test results taken at successively increasing distances between the needle-point and disc give characteristic curves for each of these oils. A new needle was fitted after each discharge, but fresh samples of oil were not used for each discharge. Against the characteristic curve for each oil is drawn the parabola $y = 0{\cdot}895\sqrt{x}$. The only point calling for comment in the foregoing table is the fact that very high specific resistances are obtained in cases H 1 and H 3, where the disruptive voltage at 100 mils is 11,000 volts or over, whereas in H 2, the lowest specific resistance of the series, the oil had a disruptive strength at 100 mils of 8,750 volts. The low disruptive voltage of 8,000 volts with a moderate specific resistance recorded for H 6 is discussed subsequently.

Methods of Testing Oil for Dielectric Strength.

In testing oils for dielectric strength it is usual to immerse two terminals or electrodes beneath the surface of the oil undergoing

Sample No.	Disruptive Voltage at 100 Mils.	Specific Resistance per Cube Centimetre. Ω.	Specific Gravity.	Viscosity.	Flash-point.	Chemical Properties.
H 1	11,000	Over 6,500,000	0·8563	27·63	176·2° C.	*Colour*—Light brown *Reaction*—Neutral *Resinoid Matter*—None (?)
H 2	8,750	666,416	0·8634	44·09	166·5° C.	*Colour*—Full lemon *Reaction*—Neutral *Resinoid Matter*—Considerable
H 3	11,250	6,500,000	0·9030	87·98	181·0° C.	*Colour*—Light sherry *Reaction*—Faintly alkaline *Resinoid Matter*—Moderate
H 4	10,250	(?)	0·9116	414·00	179·0° C.	*Colour*—Dark red brown *Reaction*—Slightly alkaline *Resinoid Matter*—Very much
H 5	10,250	1,864,000	0·8936	56·20	180·0° C.	*Colour*—Red brown *Reaction*—Slightly acid *Resinoid Matter*—None
H 6	8,000	1,541.000	0·8936	38·30	182·2° C.	*Colour*—Full lemon *Reaction*—Slightly alkaline *Resinoid Matter*—None (?)

examination at a known distance from each other, and apply a rising voltage to them till the insulating oil-gap between them breaks down by arcing through. The distance between the electrodes may be varied, and the limiting voltage found for a variety of distances. These results can be plotted on squared paper in the form of a curve. As will be shown later, the form of the curve will depend to a great extent on the shape of terminal used. The apparatus

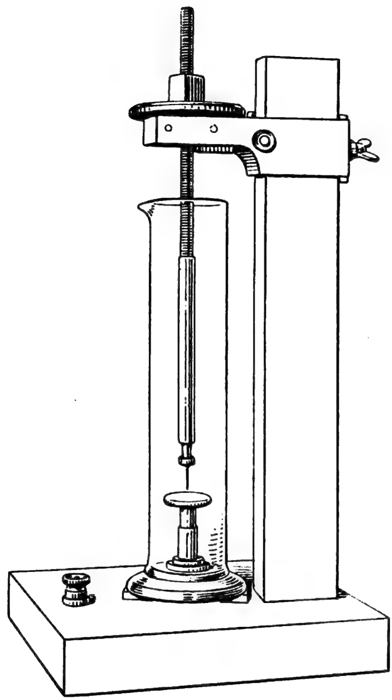

FIG. 8.

employed should embody the following features : (1) The quantity of oil required to make a set of tests should be as small as possible. (2) The electrodes should be readily interchangeable, so that various shapes can be fitted as desired. (3) The distance between the electrodes should be easily and accurately adjustable to any desired value. (4) It should be an easy matter to clean both containing vessel and terminals after a set of tests, so that there will be no danger of contamination of the next oil to be examined.

The apparatus illustrated in Fig. 8 complies with these requirements fairly well. A tall, narrow glass jar is drilled at the bottom, and a shank is passed through the hole and held in position by a nut

and leather washers. The lower end of this shank fits into a socket embedded in the stand, which is connected to a fixed terminal mounted on it. The upper end of the shank, inside the glass vessel, is arranged to support various shaped electrodes, which slide on to it. The base also supports a vertical wooden pillar, on which can be clamped at the upper end a metal piece carrying a rod which points vertically downwards to the electrode carrier fixed inside the glass vessel. The lower end of this vertical rod is arranged to carry suitably shaped electrodes, and its height, and consequently the distance between upper and lower electrodes, can be adjusted accurately by means of the micrometer head. The method of procedure when using the apparatus is to fit suitable electrodes and then to pour a definite quantity of oil into the testing vessel—say 10 oz.—and place it in position on the stand. Clamp the metal upper carrier in position and connect the two electrodes in series with a dry cell and a low reading (preferably moving coil) voltmeter. Screw down the micrometer head until the voltmeter just shows that a contact is made, set the zero of the micrometer, and by it raise the top electrode a definite amount. Disconnect the dry cell and voltmeter and connect the electrodes to the terminals of the transformer, or other source of testing voltage, which can be run up until the oil arcs through, note being taken of the voltage at which this occurs. The test can be repeated profitably a number of times over different distances, and the results plotted in the form of a curve, abscissæ representing the distances between the electrodes, and ordinates the puncturing voltages. As already mentioned, the shape of the electrodes influences the value of puncturing voltage which will be found over a given distance, and in making comparative tests with different samples of oil it is advisable to choose the terminals which give—

1. The lowest possible puncturing voltage, over a given distance; for this is the limit of what might be expected in actual, practice; and—
2. The most consistent set of results with any one oil.

It is found that with one, or both, electrodes pointed the second of these conditions is complied with, while with electrodes consisting of a point and disc respectively, the first condition is complied with. When a pointed conductor is held opposite a metallic plate, the distribution of lines of electrostatic force, or Faraday tubes, will be somewhat as shown in Fig. 9, when the plate and point are maintained at different potentials. If the difference of potential be continuously raised, the dielectric will eventually give way when the maximum value of the potential gradient reaches some critical value. Suppose now that the plate be moved a little further away from the point. With the same value of difference of potential the total number and maximum density of Faraday tubes will be slightly diminished, and to bring the latter back to its former value an increase in the difference in potential will be required. Since the density of Faraday tubes is least in the

neighbourhood of the plate (that is, the potential gradient is least) this increase in difference of potential required, expressed as a fraction of the original difference of potential, will not be as great as the increase in distance between the plate and point, expressed as a fraction of the original distance. Consequently we should expect that the curve connecting the limiting values of difference of potential between the plate and the point, and the distance between them, would bend over as the distance increased. This is obtained in practice. Again, since the Faraday tubes have a tension along their length, and their ends on the plate represent electric charges, which are free to move about, it

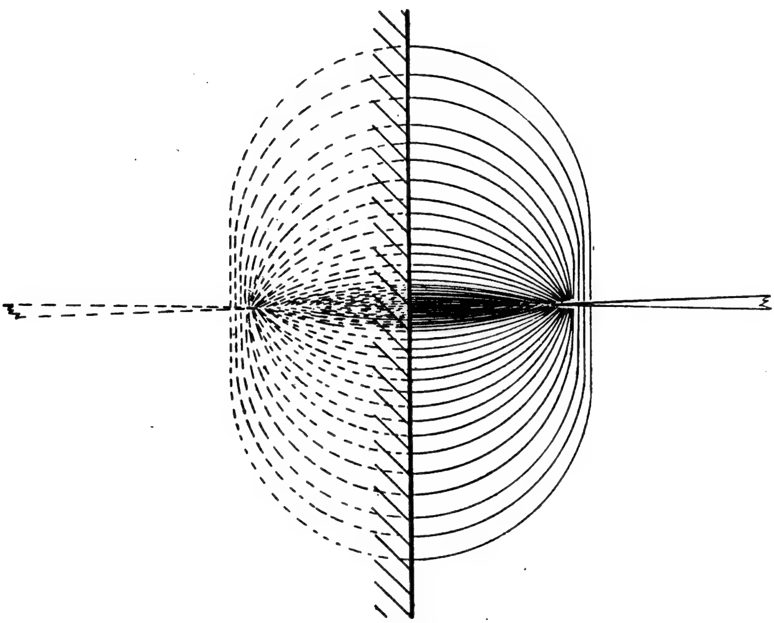

FIG. 9.

follows that all the Faraday tubes spring normally from the plate. For if they did not, the electric charges would be moved by components of their Faraday tube tensions until those components became zero. If the plate and point were exchanged from right to left, an exactly symmetrical distribution of field would occur, as indicated by the dotted lines; consequently if two points were used in the positions shown, with double the difference of potential between them that there is between the one point and plate already discussed, the distribution of field would be exactly the same, and therefore also the maximum value of potential gradient. This is a particular case of Lord Kelvin's theorem of "Electric Images." From this we should expect that the puncturing

voltage between two points would be twice that necessary to puncture half the distance between a plate and a point, and that, given the curve showing the puncturing voltage between a point and a disc, we could construct the curve showing puncturing voltage between two points. When two spheres are maintained with a difference of potential between them, and their distance apart is small, as compared with their diameter, the electrostatic field will be distributed somewhat as shown in Fig. 10. The density of Faraday tubes is fairly uniform in the space between the

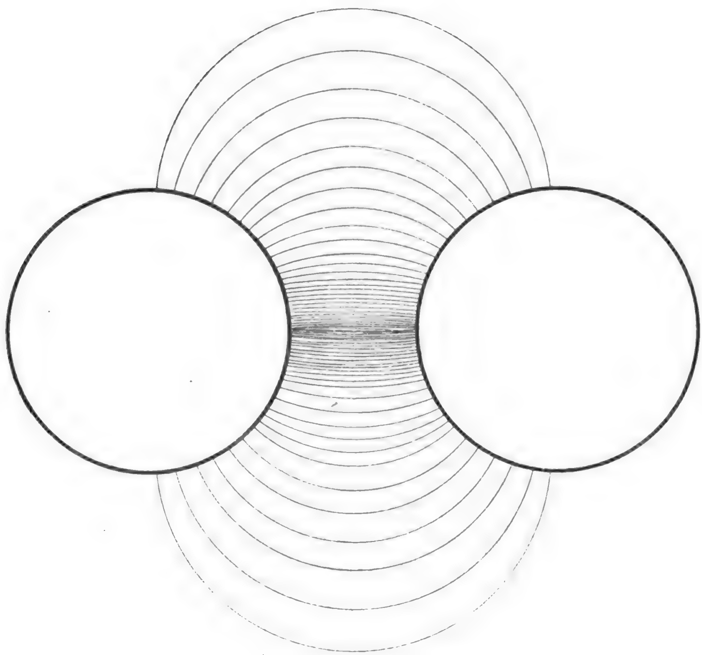

FIG. 10.

balls—that is, the potential gradient in passing from the surface of one ball to that of the other is fairly uniform. Consequently if the balls are moved slightly further apart, the increase in voltage necessary to maintain the maximum value of potential gradient will be nearly proportional to the increase in distance. From this we should expect that the curve connecting puncturing voltage and distance will be nearly a straight line when testing between balls whose diameter is considerable as compared with the distance tested over. These results are illustrated by the curves shown in Fig. 11. The lower full-line curve shows the relation between puncturing voltage and distance when testing between a point and disc. It will be observed that the experimental

points obtained lie with considerable consistency on a smooth curve. The upper full-line curve was deduced from the lower one, by taking for each ordinate double the ordinate of the lower curve at half the sparking distance. Thus, from the reasoning given above, the upper curve should represent the relation between voltage and sparking distance when testing between two pointed electrodes. The actual points obtained by experiment between two needle-points are indicated on the paper by three-legged stars, and it will be seen that they follow very

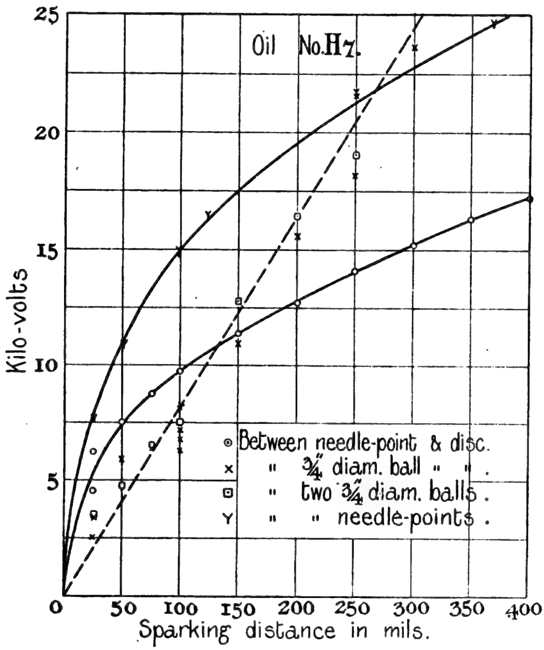

FIG. II.

closely the theoretical curve. Thus the theoretical considerations are verified. The points indicated by the squares were obtained by testing between two ¾-in. balls, and it will be seen that not only are the figures obtained much more erratic than before, but that the law which they obey is totally different, and approximates to a straight line law, as indicated by the dotted line. This also is what we have been led to expect. The points indicated by the four-legged stars were obtained by using as electrodes a ¾-in. ball and a disc, and again, as we should expect, the figures are on the whole slightly lower than those obtained between two balls. From consideration of the electrostatic fields between different shaped electrodes, as verified by the experiments just described, we see that the lowest puncturing voltages will be obtained over reasonable

distances when a point and disc are used, and as this arrangement also gives consistent readings, we adopted it for our tests. After each puncture the end of the needle-point used is fused and destroyed, so that it is necessary to fit a new needle for each reading.

Also at each puncture a certain amount of oil is decomposed, carbon being thrown down and gas escaping, to which further attention will be given. After a number of punctures have been taken on the same sample of oil it becomes quite black with the carbon in suspension, and it may be argued that it is not fair to the oil to go on making further tests on its dielectric strength after it has reached this condition. We accordingly made tests to discover how much, if at all, the oil deteriorated, and found, contrary to what might have been surmised, that even after the oil was as black as ink its dielectric strength had not appreciably weakened. In fact, we frequently found that after a puncture or two the dielectric strength improved, probably due to some slight impurities being burned out. This is in agreement with Skinner's results. To illustrate this statement the following figures give the results obtained by repeatedly testing a 10 oz. sample of oil over a 200 mil distance between a point and disc, alternatively using frequencies of 25 and 50:—

25 Periods.	50 Periods.
13,100	13,430
12,900	13,250
12,900	13,250
12,900	13,250
12,900	13,250
12,900	13,430
13,250	14,450
13,770	14,780
14,470	15,170
13,770	14,830
13,250	14,970
14,350	15,030
14,780	14,960
14,780	15,120
14,610	15,210
14,800	15,280

Temperature at start, 65° F., and at finish, 69° F.

There was a slight fall in puncture voltage after the first two tests. After that the figures were very steady for ten more punctures, when they began to go up steadily. The rise in puncture voltage in this case is probably due to rise in the temperature of the oil, which rose from 65° F. to 69° F. during the tests, due to the arcing. Further reference to the effect of temperature will be made. After thirty-two punctures the oil was certainly not weaker through carbonisation than it was at the beginning, and very consistent results were obtained for

about a dozen punctures. This number of tests is quite sufficient to obtain the curve for the sample, and we are thus justified in using the same sample, without renewal for a complete set of, say, ten readings, at successive distances of 25, 50, 75, 100, 150, 200, 250, 300, 350, and 400 mils between the needle-point and the disc.

Effect of Baking on the Dielectric Strength of Oils, with Accompanying Changes in Physical and Chemical Properties.

The oils furnishing the series of samples H 1 to H 6 were then baked for 24 hours at a temperature of 240° F., and after cooling the set of curves illustrated in Fig. 2 to Fig. 7 obtained.

The table on page 180 sets out their change in physical properties after baking, increases being indicated (+) and decreases (—).

Examining the above cursorily, the two points of outstanding interest are the increases in the disruptive voltage in four out of the six cases, and the pronounced darkening of the colour in each case. Examined in detail, we have in the case of Sample H 1 a fractional change of about 5 per cent. in the disruptive voltage, no change in specific resistance, and slight increase in specific gravity and viscosity. The decrease in the flash-point is not easily explicable.

Sample H 2 showed marked increase in the disruptive voltage and specific resistance, slight increase in viscosity, and a marked raising of the flash-point. The fall in the specific gravity, considered in the light of the other changes, suggests the presence both of traces of moisture and of a large proportion of volatile oils.

Sample H 3 shows an increase of less than 5 per cent. in the disruptive voltage, with slight increases in viscosity and specific gravity and a marked raising of the flash-point. The decrease in the specific resistance while apparently large is in reality of small moment, as when high degrees of purity are reached a minute accidental trace occasions a marked lowering of the value. Some trifling accidental contamination is probably the reason for this.

Sample H 4 shows an increase of nearly 10 per cent. in the disruptive voltage, with the heaviest increase of the series in the specific gravity and viscosity. Possibly slight traces of acid together with the large quantity of resin present have facilitated changes in the oil which are further exemplified by the very marked colour change.

Sample H 5. The fall in disruptive strength of this sample is somewhat difficult to explain. The increases in specific gravity and viscosity are not so marked as in H 4. The colour changes are every bit as marked as in H 4, but the absence of resinoid material does not permit our ascribing the colour change to the agency of resin.

Sample H 6 is interesting as having its disruptive voltage increased by over 35 per cent. as the result of the baking, together with a raising of the specific resistance by 800,000 megohms. The slight fall in the specific gravity coupled with a flash-point only raised a few degrees, points to the initial presence of slight traces of moisture which were

Sample No.	Disruptive Voltage at 100 Mils.	Specific Resistance, ω.	Specific Gravity.	Viscosity.	Flash-point.	Chemical Properties.		
						Colour Change.	Reaction.	Resinoid Matter.
H 1	− 650	Unchanged	+0·0037	+ 0·17	−17·7° C.	Light lemon to medium sherry ...	Very faintly alkaline	Slight
H 2	+1,250	+1,176,900	−0·0021	+ 3·41	+25·5° C.	Full lemon to light sherry	Neutral ...	Moderate
H 3	+ 500	−3,858,500	+0·0028	+ 2·72	+17° C.	Light sherry to dark olive brown ...	Distinctly alkaline	Moderate
H 4	+1,000	Decrease: extent not determined	+0·0052	+33·70	+19·5° C.	Dark red brown to very dark olive brown	Slightly acid	Consider-able
H 5	−1,000	−1,013,300	+0·0011	+10·35	+23·25° C.	Red to very dark olive brown ...	Very slightly acid	None
H 6	+3,000	+ 886,300	−0·0006	+ 3·90	+ 4·5° C.	Full lemon to dark olive brown ...	Neutral ...	Moderate

expelled with a very small quantity of oils volatile at less than 240° F. The change in the viscosity is quite small.

Reviewing, therefore, the effect of baking this series of oils, we have the following general deductions :—

1. An increase in the disruptive voltage where this was less than 10,000 volts over the test distance.
2. No increase in specific resistance for oils of high specific resistance, but an increase of specific resistance in those cases where decreases in specific gravity indicate the expulsion of moisture.
3. A general increase in specific gravity and viscosity, and a raising of the flash-point, due to the evaporation of the more volatile constituents.
4. Marked changes in the colour of the oil, in each case of a darkening nature. This is probably due to the evaporation mentioned above, coupled with molecular regroupings of the constituents.
5. A tendency to emphasise the indications of any traces of alkali, the change being from neutral to very faintly, or from faintly to distinctly alkaline.
6. Irregular behaviour in regard to the indications of the presence of resinoid matter. This varies with the nature of the oil, and is probably worth further investigation.

Physical Examination of Oils.

The physical examination comprises determinations of the specific gravity, the viscosity, the flashing-point or temperature at which the oil gives off an inflammable vapour, the specific electric resistance and dielectric strength. The specific gravity may be taken by means of a specific gravity bottle and the balance; but the high coefficient of expansion of oils necessitates very careful attention to the temperature. The hydrometer, if delicate, may also be employed, but a very satisfactory method of determining the specific gravity is afforded by the Westphal balance (see Fig. 12). A glass plummet containing a small thermometer is suspended by a very fine platinum wire from the end of a graduated balanced lever, and on being immersed in the oil contained in a glass cylinder loses weight; equipoise is brought about by placing on the graduated arm rider weights so adjusted as to give direct readings, which are quite equal in delicacy to results obtained by the balance and specific gravity bottle, and decidedly superior to those obtained by the hydrometer.

The viscosity is best ascertained by the Redwood viscosimeter (Fig. 13) which consists of an inner tube of thickly silver-plated brass or copper 3 in. high, by $1\frac{7}{8}$ in. internal diameter, having at the centre of its lowest point an orifice of defined size in an agate cup, which orifice can be closed either by the bulb of the thermometer or by a ball plug attached to a wire. Near the top of the interior of the tube a metal

point is fixed to indicate the exact height to which the oil should reach, so as to start the experiment with an invariable head of oil. This tube is surrounded by a cylindrical vessel of copper, and the temperature of the inner tube is regulated by that of the water or other liquid contained in this outer vessel. A cylinder of thin copper, closely surrounding the inner tube, is furnished with inclined paddles which afford the means of thoroughly agitating the liquid in the outer vessel, a handle being attached to the top of the curved rim for the purpose of revolving this mechanism. The outer vessel is provided on one side with a tube depending at an angle to which a flame can be applied for the purpose of increasing the temperature, and on the other side with an outlet tube furnished with a tap. The whole apparatus is mounted on a tripod stand with levelling screws. The determination of viscosity is effected by filling the inner vessel to the top of the metal-point with the oil to be examined, which is then brought to the required temperature, usually 15·5° C., and when the thermometers in the inner and outer vessel are both steady at the desired temperature a 50-c.c. graduated flask with a narrow neck is placed under the hole in the agate cup, the valve plug removed, and the time noted in which 50 c.c. of the oil runs through. The viscosity is then calculated by multiplying the time in seconds by 100 and by the specific gravity, and dividing the product by 489·525, a constant arrived at by taking the time for pure rape oil (having a viscosity of 100) as 535 seconds, and multiplying this figure by 0·915, its specific gravity. Very great care must be taken to ensure the temperature remaining constant during the time the oil is running out, as a variation of even ½° F. will cause an appreciable difference in the result when viscosity is high. The flashing-point of such oils as are now under consideration is best ascertained by some such apparatus as the Martin-Pensky, shown in Fig. 14. The oil to be tested is placed in a tinned brass cup furnished with a lid having a revolving cover, in which are three open spaces, the middle one of which permits a small gas jet giving a bead-flame having a diameter of about 0·12 in. to be depressed through the opening into the oil-cup at regular intervals by a motion of the head of the vertical handle. The oil-cup must always be filled to a constant height of about 15 mm. from its upper rim, and is placed in a cast-iron well, of such dimensions as to leave an air-space between it and the oil-cup, attached to the outer dome. Beneath the cast-iron well a ring covered with stout gauze serves to equalise the heating action of the powerful Bunsen burner supplied with this form of apparatus. In taking a test it is requisite that when the neighbourhood of the expected flashing-point is reached the temperature should be so regulated as to rise only about 1° per minute, whilst the oil must be kept constantly agitated by rotation of the stirrer through the flexible attachment which is readily manipulated by the fingers. The aperture in the cover of the oil-cup should be gradually opened during a period of 3 seconds and closed in the fourth second. When an appreciable quantity of an

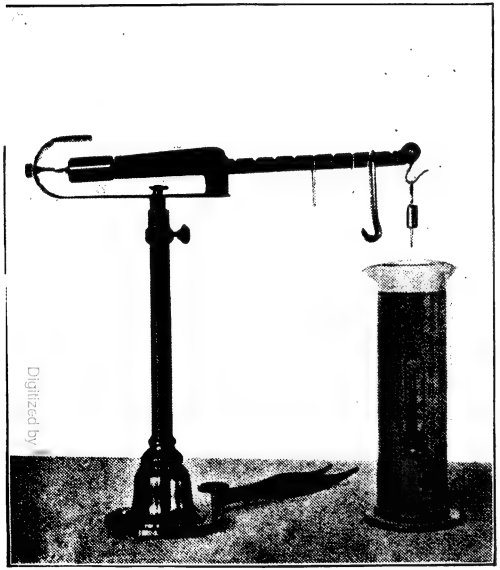

FIG. 12.

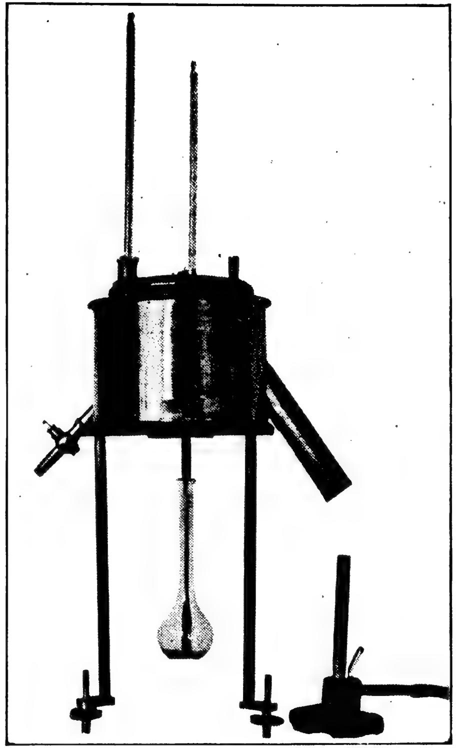

FIG. 13.

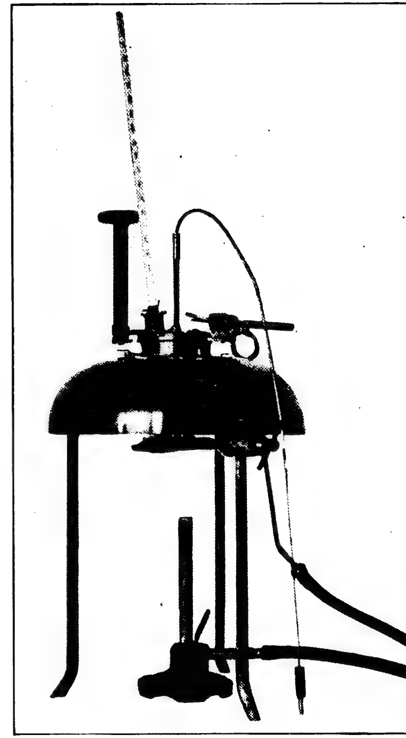

FIG. 14.

inflammable vapour is being given off a sharp blue flash will be observed on the bead-flame being depressed into the oil-cup. A check reading should be taken as the temperature falls, and the flashing-points with temperature rising and with temperature falling should be almost identical.

The coefficient of expansion of petroleum varies inversely as the specific gravity. A. H. Allen gives the following figures:—

Specific Gravity at 15° C.	Expansion Coefficient for 1° C.
Under 0·700	0·00090
0·700 to 0·750	0·00085
0·750 to 0·800	0·00080
0·800 to 0·815	0·00070
Over 0·815	0·00065

Chemical Examination.

In many instances it is desirable to ascertain the nature of oil intended for use in switches and transformers, and to establish its freedom from impurities and additions which might make it unsuitable or might tend to cause deterioration. The oil should be pure mineral oil, free from moisture or any notable proportion of oils of low boiling-point, alkali, acid, sulphur and its compounds, resin, fatty oils, tarry matter, and metallic soaps. Colour is not always an index of quality. A dark-coloured oil may be quite pure, but is less likely to be so than an oil of a golden shade. Fluorescence is a usual characteristic of most mineral oils, but is entirely absent in some. Odour, cold or on warming, if pronounced, indicates imperfect refining or undesirable volatile compounds. Turbidity may be caused by the presence of water or of solid hydrocarbon bodies. In the first case, frothing generally ensues on heating; and in the other, solution would take place. Turbidity may also arise from suspension of insoluble solid matter. Moisture may be detected by means of exsiccated cupric sulphate, which is coloured blue by the slightest trace of water. The rough-and-ready test by immersion of a strongly heated bar of metal is also useful. The amount of moisture and oils of low boiling-point is determined by the loss of weight at 100° C. First-class oils rarely show a greater loss than 0·3 per cent. in six hours; and when the figure exceeds 0·5 per cent. the flashing-point or the specific resistance may be low.

Alkali and acid, if present, are found by shaking the oil with an equal bulk of boiling water in a separator or a closed tube, which is then maintained at a temperature of 98° C. to 100° C. until separation is complete, when the aqueous liquid is tested with suitable indicators. Phenol-phthalein is not reliable, and is not affected by the soaps of alkali metals; whilst methyl-orange cannot be used with hot liquids. Tincture of cochineal prepared with 20 per cent. alcohol is most generally suitable. In neutral solutions its colour is red; alkali produces a violet purple, and acid gives a yellow colour. When used with due care it is very sensitive. Alkali (soda) is also indicated by

the production of a milky white emulsion; whilst resin is precipitated in fine, white granules, which form a well-defined band at the point of separation of the oil from the water. A. H. Allen, in his "Commercial Organic Analysis," states that "alkali is often purposely left in an oil with the view of increasing its 'body' or viscosity. This is effected by blowing air through the imperfectly washed oil. As the moisture is got rid of the oil takes up the soda while remaining perfectly transparent. Such oil is very prone to oxidise, and becomes turbid on exposure to air from absorption of moisture. It is also liable to change in colour." The authors have found that slight traces of alkali are liable to cause deterioration in the specific resistance in consequence of absorption of moisture.

A portion of the separated water used to extract acid and alkali is tested for sulphuric acid and sulphonates by addition of solution of baric chloride.

Sulphur may be identified by applying the nitro-prusside test to an aqueous extract separated after the oil has been subjected to the action of metallic sodium. The slightest trace of sulphur gives an intense violet-blue colour. This test should not be attempted by those who have not had chemical training. Sulphur compounds give a brown colour on addition of silver nitrate to a slightly ammoniacal extract from a heated mixture of the oil with alcohol. Fatty oils and resin are indicated by the acrid or resinous odour given off when the oil is heated until its vapour ignites and the flame blown out. The fatty oils are definitely detected and their amount estimated by saponifying the oil, washing the aqueous soap solution with ether, and separating the fatty acids. Resin may be approximately estimated by agitating the oil with fairly strong alcohol, which is then separated and evaporated to dryness. Free fatty acid would be extracted from the oil by alcohol; but it is not likely that any would be present. Resin gives a brown colour to caustic soda. If the oil contain tarry matter, it is detected by agitating the oil with an equal volume of solution of caustic soda of specific gravity 1·36 and separating at 55° C. The tar, etc., will be precipitated.

Mineral impurities and additions will be found in the ash left on ignition of the oil. Alkali-metal soaps leave an ash having a strong alkaline reaction; and any free fixed alkali (soda) existing in the oil would give a similar result. Oleate and palmitate of aluminium are occasionally added to mineral oils to increase the viscosity; and the ash from such oil contains oxide of aluminium in sufficient quantity to give proof of the presence of aluminium. Aluminium soap may also be found by extracting the oil with ether and dilute acid. The addition of ammonia to the separated and filtered aqueous liquid gives the characteristic precipitate of aluminium hydrate.

Relation of Dielectric Strength to Temperature.

The fact of the variation of specific resistance with temperature suggested to the authors the advisability of studying the relation

between temperature and dielectric strength. For this purpose the needle-point and disc were set at a distance of 100 mils and the temperature gradually raised to about 300° F. The time occupied in heating was about one hour. The temperature was then allowed to fall, an operation taking about the same time. The dielectric strength was tested during both the heating and cooling periods. In only two out of the six cases were points given on cooling identical with the heating curve. In these two cases the specific resistance of the oil as supplied was very high indeed.

The table on page 186 sets out the main results of this investigation.

A comparison of the variations of the dielectric strength with temperature with the changes in the physical properties produced by baking for twenty-fours at 240° F. shows that the three classes under which their behaviour after dielectric tests at varying temperature falls bears a distinct relation to the other properties of the oil. We have, first of all, the oils having identical dielectric strength curves on heating and cooling—viz., H 1 and H 3—which were oils of high specific resistance and fair purity. Secondly, there are oils giving a higher dielectric strength on fall of temperature, such as H 2 and H 6. These were oils whose specific resistance and dielectric strength were improved by baking, and which probably contained moisture. Thirdly, there was sample H 5, which gave a lower dielectric strength on fall of temperature; this oil fell in disruptive strength after baking. Sample H 4 behaved very irregularly; at its initial chemical examination it was found to contain large quantities of resin and slight traces of acid.

It is obvious from these tests that for all oils the dielectric strength increases with increasing temperature, but that consistent readings on the ascending and descending temperature curves are only obtained by oils of high specific resistance, *i.e.*, pure oils. This fact of increase of dielectric strength with temperature throws a grave doubt on the soundness of the general practice of nearly all makers of oil-cooled transformers, who apply lower test pressures to the transformer when heated at the end of a test run, than when it has been allowed to cool down.

The Relation of Viscosity to Temperature.

The "body" or viscosity of oils is very materially affected by variation of temperature. They all become thinner with increase in temperature, and the higher the viscosity at ordinary temperatures the greater is the effect of heat in reducing the viscosity. The specific gravity of an oil is quite valueless as an index of its viscosity. The specific gravity of a pure oil is dependent on the atomic structure of the molecule; but the viscosity is most probably determined by the molecular grouping. The viscosity of Russian mineral oils is greater than that of American mineral oils of the same specific gravity; and

Sample No.	Specific Resistance Megohms per Cubic Centimetre.	Dielectric Strength at 60° F.	Dielectric Strength at 120° F.	Dielectric Strength at 180° F.	Dielectric Strength at 240° F.	Remarks.
H 1	Over 6,500,000	11,200	12,800	15,600	21,400	One curve covers observation during heating and cooling (see Fig. 15).
H 2	666,416	r 10,800 f 11,600	r 12,400 f 14,500	r 15,200 f 18,000	r 18,800 f 23,200	Separate curves for heating and cooling, higher dielectric strength on fall of temperature (see Fig. 16).
H 3	Over 6,500,000	10,800	12,600	14,800	18,000	One curve covers observations during heating and cooling (see Fig. 17).
H 4	—	9,800	11,000	12,300	13,600	Results are those from curve (see Fig. 18). Observations very irregular.
H 5	1,864,000	r, f 9,200	r 12,400 f 10,800	r 14,600 f 12,200	r 19,000 f 13,800	Separate curves for heating and cooling, lower dielectric strength on fall of temperature (see Fig. 19).
H 6	1,542,000	r 9,800 f 11,600	r 13,000 f 14,400	r 16,000 f 19,600	r 18,400 f 24,000	Separate curves for heating and cooling, higher dielectric strength on fall of temperature (see Fig. 20).

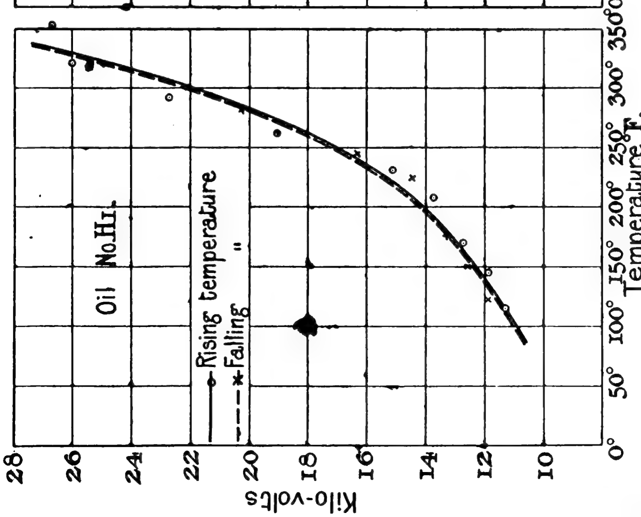

FIG. 15.

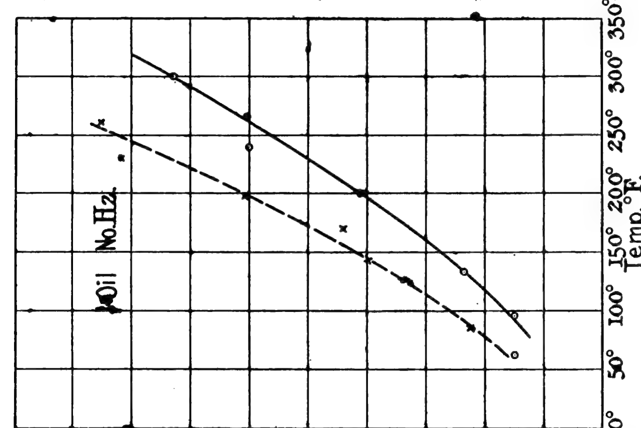

FIG. 16.

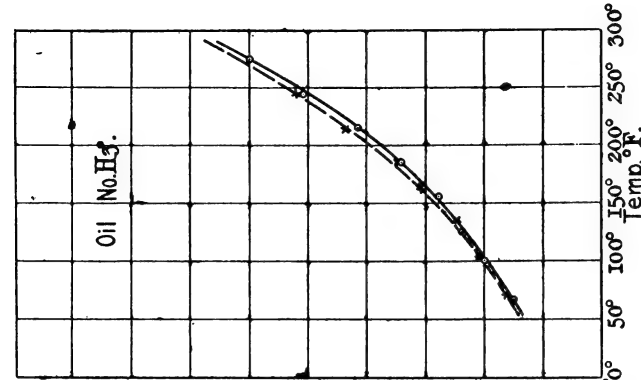

FIG. 17.

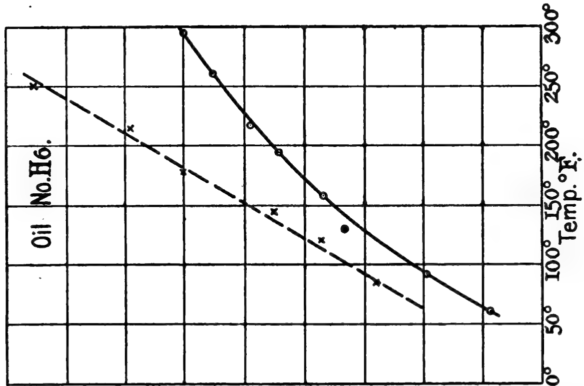

FIG. 20.

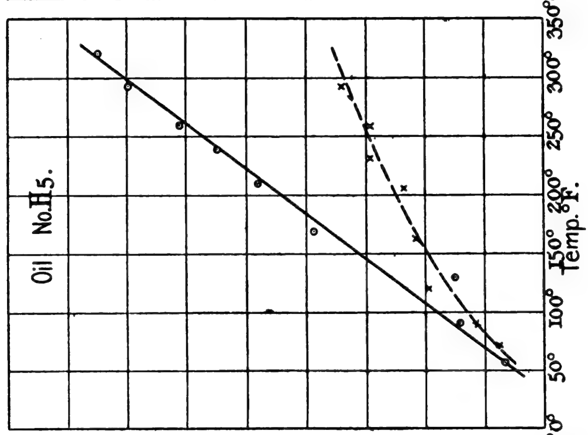

FIG. 19.

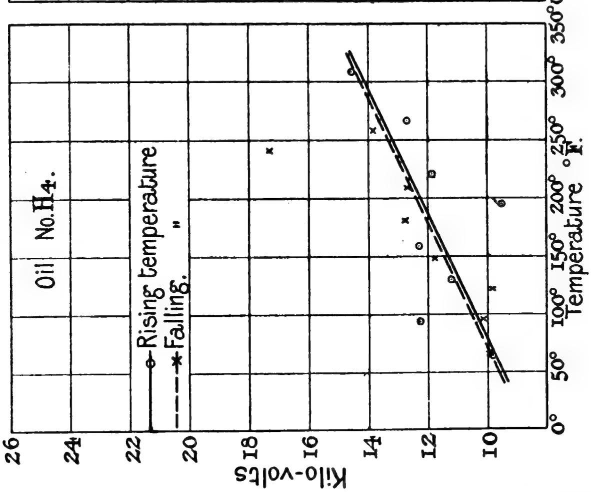

FIG. 18.

for equal increments of temperature the viscosity of the Russian oils falls to a greater extent than that of the American oils.

A sample of a well-known brand of switch and transformer oil, of American origin, of the class referred to in this paper as H 1, having a specific gravity of 0·8588 at 60° F., examined in the authors' laboratory, gave the results stated in column A of the following table; and columns B and C show the varying viscosities of (B) American oil of specific gravity 0·913 at 60° F. and (C) Russian oil of specific gravity 0·915 at 60° F., calculated from results published by Boverton Redwood. The oil B approximates to that which is designated elsewhere as H 5.

t° F.	A. Viscosity.	B. Viscosity.	C. Viscosity.
60·0	25·40	55·11	370·9
80·0	16·37	31·66	167·2
100·0	11·41	20·42	81·23
120·0	9·18	14·25	44·92
140·0	7·83	10·52	26·40
160·0	6·84	8·29	16·91
180·0	6·27	—	12·12
198·5	5·89	—	—
200·0	—	—	9·63

It will be seen that at 60° F. the viscosity of B is, roughly, double that of A; but at 120° F. is only about 50 per cent. greater, whilst the difference rapidly diminishes at still higher temperatures (see Fig. 21).

The viscosity of transformer oil should be low enough to ensure free convection with a moderate rise of temperature, above 60° F.; nevertheless an allowance for the lowering of the viscosity when the oil becomes warm may be made in deciding on the suitability of an oil for use in transformers. The viscosity at 60° F. should be regarded as the index. Taking 130° F. as the temperature, which is frequently attained in a transformer under average conditions in the English climate, it is manifest that an oil which would not quite afford free play to convection currents below 100° F. might be as satisfactory as one possessing the requisite degree of mobility at 70° or 80° F. Of course, the heating of transformers varies with the working conditions, and it is therefore difficult to fix the maximum viscosity permissible. As a rule, however, a viscosity higher than 70 or 75 is undesirable unless atmospheric temperature, load, and duration of running are such

that high temperatures are inevitable. Where such conditions do not arise a viscosity not exceeding 45 to 50 is to be preferred. Given equality in other respects, oils having the lowest viscosity should be selected for transformers.

For switches, too, the use of an oil having a viscosity sufficiently high to prevent or seriously to impede the subsidence of suspended matter is to be avoided. Considered electrically, the authors have not yet satisfied themselves as to whether—other factors being equal—

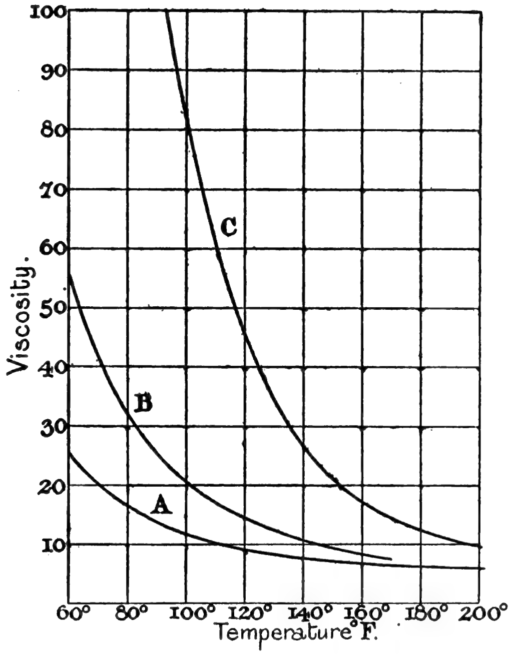

FIG. 21.

thin or thick oils are to be preferred. So far as temperature is concerned in well-designed switchgear with no local heating and infrequent opening, the temperature of the switchboard gallery alone calls for consideration. The function which the oil has to serve is either that of preventing the formation of the arc or of quenching it when struck. In effecting this the decomposition of the oil should be as small as possible. From the theoretical point of view, a heavy oil should hinder the formation of an arc owing to its molecular tenacity, while a thin oil with a more rapid rate of flow would probably be quicker in extinguishing the arc. The authors hope to be able to investigate this subject by means of the oscillograph at a later date.

Variations in the Properties of Oils forming a Single Consignment.

The authors have already stated that while flash-points and viscosities of samples taken from a number of drums agreed very closely with the makers' guarantees, dielectric strength varied very widely from this. An excellent example of this is afforded by an instance arising in the course of the routine testing carried out by one of the authors. The consignment was small in quantity, being only about 800 gallons, and was supplied to the following specifications: "A fluid oil of high dielectric strength, with a flash-point over 177° C., absolutely free from water, sulphur compounds, acids, and alkalies, to be supplied. . . . A dielectric strength of 14,000 volts to be obtained between needle-points $\frac{1}{8}$ in. apart. . . ."

Ten samples were taken from 10 out of the 21 steel drums containing the oil. The table on page 192 sets out the properties of the samples.

Three of the above drums were rejected on the dielectric tests, and as these tests were of the everyday commercial order, other tests were not taken. But as these failures represented 30 per cent. of the quantity sampled, and 15 per cent. of the entire order, this indicates the necessity of examining each drum or cask if the properties called for in a specification are actually required, and the latter is not to be relegated to the category of very excellent literature which may be piously perused and then pigeon-holed.

The Effect of a Series of Disruptive Tests on Chemical and Physical Properties.

Primarily the effect of a high-tension discharge through an oil is to char part of it, converting a portion of the hydro-carbon into an amorphous carbon in the shape of minute particles with the liberation of a small bubble of gas. These particles first appear in the form of a cloud. Segregation of the particles ensues followed by sedimentation, the rate of which is by no means constant. Samples of oil from a consignment of the same brand, after flashing, have been found cloudy owing to carbonaceous matter in suspension after standing untouched for a week, whereas other samples from the same consignment are relatively clear in one or two days, the minute particles having coalesced to form distinct granules at the bottom of the vessel. This difference in behaviour is a little difficult to explain, as in each case the same automatic switch broke the primary circuit of the transformer on sparking taking place. With minute particles of carbon remaining in suspension after several days settling, it is quite natural that the specific resistance should fall in value, and that the viscosity and specific gravity should be increased. The series of six special samples of oils submitted to dielectric tests both in their condition as received, and also after baking, as already described, were carefully examined in the laboratory in order to determine whether there was any marked divergence between them.

Sample No.	Specific Gravity.	Viscosity at 15·4° C.	Flash-point. °C.	Specific Resistance, Ω.	Dielectric Strength. Needle-points ⅛ in. Apart.	Reaction.
2	0·8590	26·10	176·0	2,495,000	14,400	Very slightly alkaline
3	0·8597	26·25	175·5	Not taken	11,000	Very slightly alkaline
4	0·8590	26·50	175·5	2,679,000	14,300	Slightly alkaline
5	0·8600	26·70	175·5	2,421,000	14,600	Very slightly alkaline
6	0·8605	26·90	175·5	3,857,000	15,100	Neutral
7	0·8570	26·10	175·5	1,507,000	13,970	Moderately alkaline
8	Not examined				8,200 11,600	Not examined
9	Not examined				11,500	Not examined
10	0·8588	25·40	175·5	Over 6,500,000	14,600	Moderately alkaline
11	0·8584	26·18	175·0	6,500,000	16,100	—

The table on page 194 sets out the changes in the properties of the unbaked oils set up through their having undergone a series of disruptive tests. The specific resistance has fallen in each case, but not in any uniform ratio. In only two cases (H 2 and H 6) has the specific gravity been reduced, this sample, No. H 2, being singular as having fallen in specific gravity during baking.

The dielectric test has apparently served to expel moisture from the oil. Viscosities are uniformly higher. The flash-point is abnormally lower for H 2, only slightly changed for H 1, H 3, and H 6, and higher for H 4 and H 5. The colour changes are distinct in H 3 from light sherry to dark olive, and darker for H 4 and H 5. As regards their chemical properties, the considerable resinoid matter originally present in H 2 disappears, but in H 6 a very dubious trace of resinoid matter becomes considerable. Similarly the changes in regard to alkalinity are not uniform. For instance, H 1 became distinctly alkaline, being previously neutral; H 4 changed from slightly alkaline to distinctly alkaline.

The table on page 195 shows the changes produced in the baked oils through their having undergone a series of disruptive tests.

There is again a distinct fall in specific resistance, while specific gravities are higher in four cases and lower in two. In these last-named instances the viscosity rose, whereas the increased specific gravity was accompanied by a decreased viscosity. Flash-points have been irregular, falling in four cases and rising in two. Of the colour changes one only is remarkable, namely H 1, where the oil reverted to its colour before baking. As regards the reaction, there are no changes in H 1 and H 2, but in H 3 a distinct alkaline reaction gives place to one very faintly alkaline, while in H 4 and H 5 slight and very slight acid reactions give place respectively to very distinct and distinct alkaline indications. In H 6 a neutral reaction changed to one slightly alkaline. The changes in the indication of resinoid matter are inconsiderable.

Changes in Physical and Chemical Properties of Oil in Switch Tanks.

Inasmuch as the results of an investigation of the changes in different oils (both baked and unbaked) after dielectric test were interesting and suggestive rather than instructive and positive, the authors then arranged to study the properties of oils of the classes H 1, H 3, and H 5 after their use in extinguishing an arc due to a given current broken a definite number of times in an oil break switch. For this purpose Messrs. Mather and Platt, Ltd., kindly placed at their disposal a 30-B.H.P. 3-phase 440-volt motor. This was loaded up until the current per phase was exactly 35 amperes, when the switch was tripped and the current broken at six points below the surface of the oil two hundred times in succession for each of the three oils.

Sample No.	Specific Resistance, ω.	Specific Gravity.	Viscosity	Flash Point. °C.	Chemical Properties. Colour Change.	Chemical Properties. Reaction.	Chemical Properties. Resinoid Matter.
H 1	−6,000,000	+0·0017	+1·32	− 2·7	None	Distinctly alkaline	None (?)
H 2	− 229,100	−0·0014	+0·64	−40·5	None	Neutral	None
H 3	−6,400,000	+0·0017	+4·43	+ 3·5	Light sherry to dark olive ...	Slightly alkaline...	Slight
H 4	(?)	+0·0004	+4·65	+19·25	Dark red brown to very dark red brown...	Distinctly alkaline	Much
H 5	−1,687,000	+0·0007	+5·97	+12·25	Red brown to dark red brown ...	Moderately acid...	None
H 6	−1,100,000	−0·0008	+0·60	− 4·0	None	Very faintly alkaline ...	Considerable

Sample No.	Specific Resistance, Ω.	Specific Gravity.	Viscosity.	Flash-Point. °C.	Chemical Properties.		
					Colour Change.	Reaction.	Resinoid Matter.
H 1	−6,000,000	−0·0015	+ 0·26	+10·50	Medium sherry to lemon ...	Slightly alkaline	Very slight
H 2	−1,577,000	+0·0027	− 1·80	−42·00	Light sherry to light brown sherry ...	Neutral	Very slight
H 3	−2,430,000	−0·0018	+ 7·90	− 6·00	Dark to very dark olive brown ...	Very faintly alkaline	Moderate
H 4	−1,219,000	+0·0012	−12·40	+ 4·50	None	Very distinctly alkaline ...	Very much
H 5	− 104,400	+0·0002	− 1·76	− 2·25	None	Distinctly alkaline	Much
H 6	−1,436,000	+0·0010	− 1·48	−10·75	None	Slightly alkaline...	Very slight

The object of the tests was:—

1. To ascertain the progressive rate of fall of specific resistance due to carbonisation.
2. To ascertain the progressive change in reaction and indications of traces of resinoid matter.
3. To ascertain the relative changes in the important factors of viscosity, and flash-point in the respective oils at the end of the given number of times of breaking the circuit.
4. To ascertain the total weight and nature of the carbon produced in the three oils at the end of the given number of times of breaking the circuit.

The oils used were delivered by the firms supplying the types H 1, H 3, and H 5, and were fairly typical of the classes of oil in question. The authors have already pointed out the great variation which occurs in oils of the same brand forming part of the same consignment. It was therefore considered advisable to obtain curves of the dielectric strength of these oils, together with their other properties before use. Figs. 22 to 24 give their initial dielectric strength, and the following table their other initial properties:—

Class of Oil.	Specific Gravity.	Flash-point. ° C.	Viscosity.	Specific Resistance. Megohms.	Colour.	Reaction.	Resinoid Matter.
H 1	0·856	177	25·5	Over 6,500,000	Light golden yellow ...	Faintly alkaline	None
H 3	0·903	202	96·5	Over 6,500,000	Light sherry	Faintly alkaline	None (?)
H 5	0·872	193	66·0	Over 6,500,000	Red brown	Faintly alkaline	Trace

After the above tests, curves showing their terminal dielectric strength were obtained (see Figs. 22 to 24). Their other properties are shown in the following table:—

Class of Oil.	Specific Gravity.	Flash-point. ° C.	Viscosity.	Specific Resistance. Megohms.	Colour.	Reaction.	Resinoid Matter.
H 1	0·856	177	25·5	2,828,000	Light golden yellow ...	Neutral	Very distinct
H 3	0·900	204	94·7	945,000	Light sherry slight turbidity ...	Neutral	Slight
H 5	0·872	204	71·3	Over 6,500,000	Red brown	Practically neutral.	Trace

To a certain extent the above tests are inconclusive in that they do not show any very marked changes. On the other hand, they do indicate what a very efficient piece of apparatus a good oil switch may be,

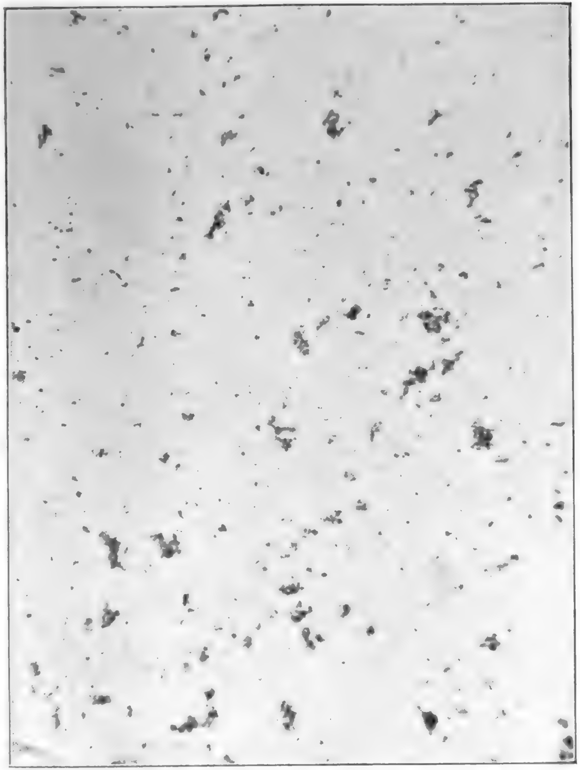

FIG. 25.—H 1 (125 magnifications).

FIG. 26.—H 3 (125 magnifications).

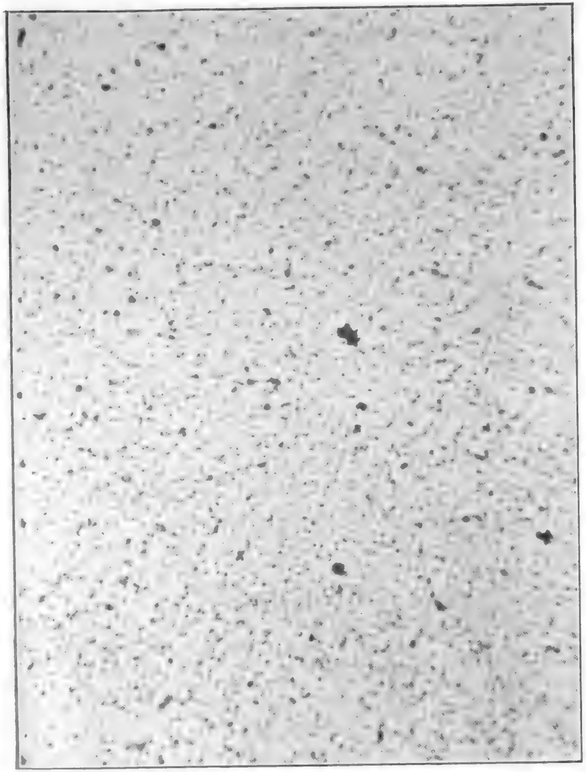

FIG. 27.—H 5 (125 magnifications).

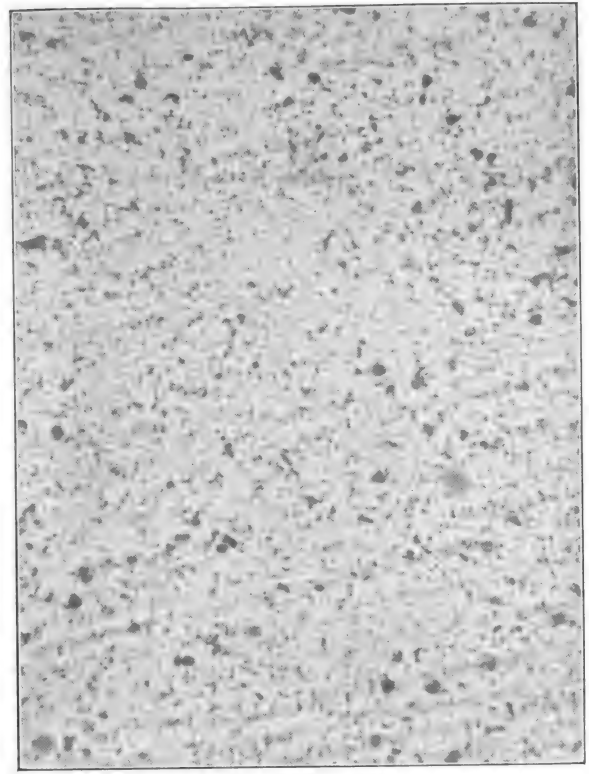

FIG 28.—H 5 (250 magnifications).

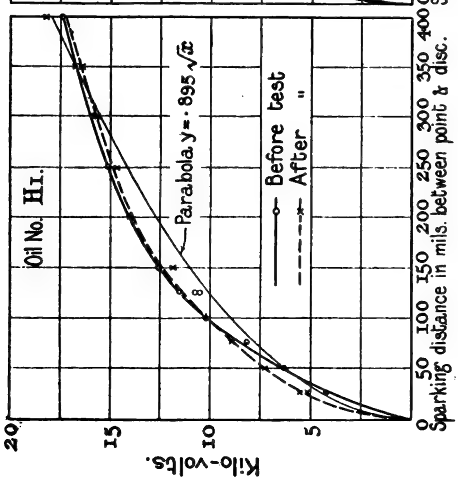

FIG. 22.

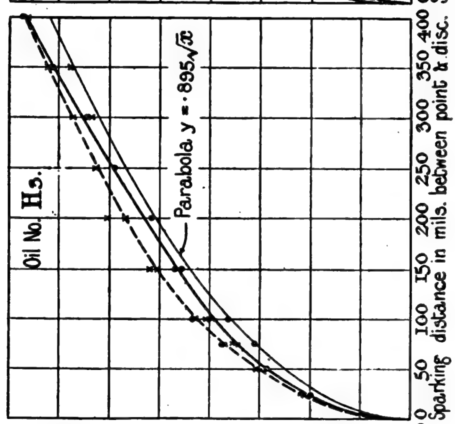

FIG. 23.

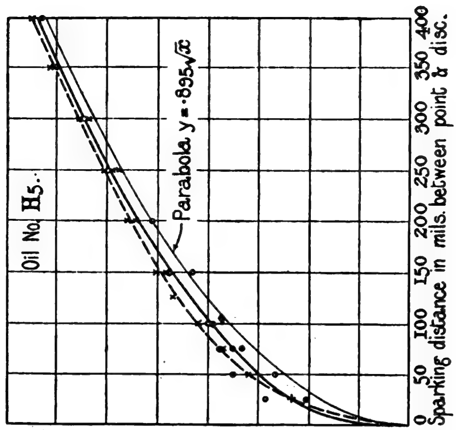

FIG. 24.

and certainly tend to prove that with good oil, and protection from the ingress of dust or moisture, such a switch might be tripped a great many times before the physical properties of the oil fell below those of a number of the inferior oils only too often used. The changes which actually occurred include a tendency to a fall in specific resistance, with increases in the viscosity figure, and raising of the flash-point. These results are quite normal and could have been deduced from the investigation of the effect of dielectric tests upon physical properties. In one respect only the authors did not find the result they had anticipated. They had hoped to ascertain the relative rates of carbonisation of these oils, but no carbon was visible, while the high specific resistance precluded the presence of anything save indeterminable quantities of conducting materials.

The Effect of Prolonged Arcing.

On account of the negative results arising from the investigation just described, the authors decided to try the effect of maintaining an arc between a copper ball and disc at a definite distance for a set time.

The pressure selected was 10,000 volts, the sparking distance 60 mils, and time 180 seconds. So far as could be calculated the current flowing in the high-tension circuit of the transformer was 110 milliamperes. Visually there was a pronounced darkening of the oils which received this test—namely, H 1, H 3, and H 5. Microphotographs of the carbon in suspension were prepared, and the results are indicated in Figs. 25 to 28. In each case the carbon produced is entirely of the amorphous variety. One salient difference does exist, namely, that in oil H 1, which had the lowest specific gravity of the three, segregation of the carbon particles takes place, and their greater size is easily apparent on the photographs. Visually, moreover, the authors had noticed that sedimentation occurs in this oil more rapidly than with oils of higher specific gravity.

The amounts of carbon were determined in these three oils with the following results :—

H 1	... ...	0·00533 gramme per 100 c.c.
H 3	... ...	0·02900 „ „
H 5	... ...	0·02050 „ „

Effect of Temperature Upon Specific Resistance.

Unless otherwise mentioned, all specific resistances quoted in this paper are at a temperature of approximately 60° F. The authors were aware, both from the work of previous investigators and from experience of the use of oils in connection with cellulose materials for general insulation purposes, that a rise of temperature involved a fall in insulation resistance. As has already been shown, prolonged heating at 240° F. for twenty-four hours, while serving to expel moisture in the case of oils containing moisture, had the effect in the case of dry

oils of causing a change in the physical properties, It was therefore decided to limit the temperature to which the oil should be raised, as well as the time of application in the case of an investigation of the

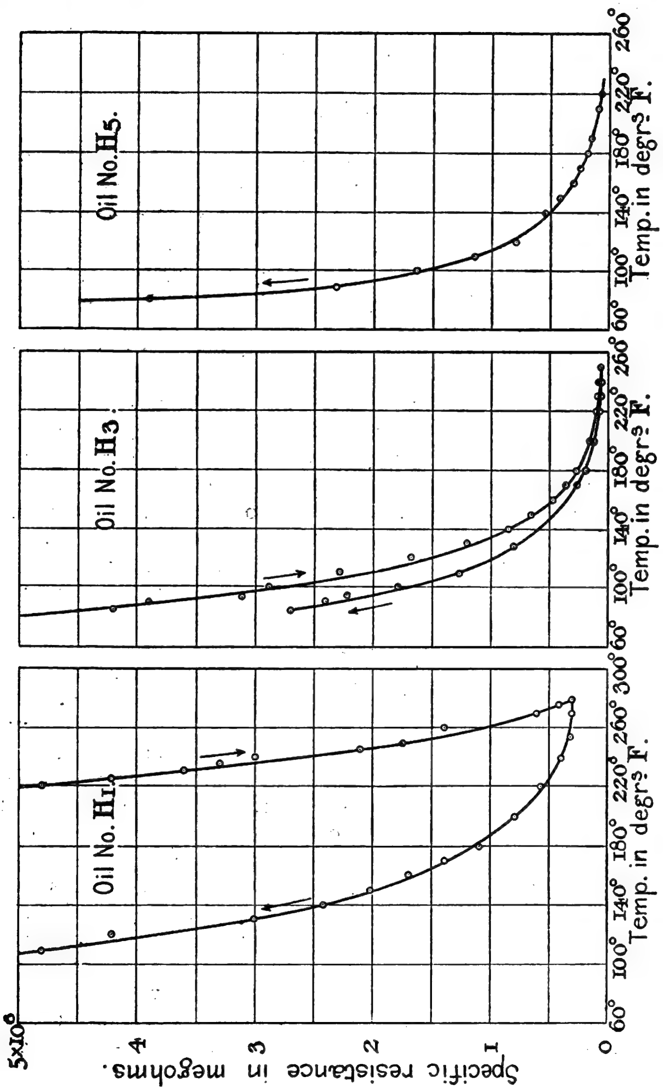

FIG. 29. FIG. 30. FIG. 31.

relation between temperature and specific resistance. Three different oils of types Nos. H 1, H 3, and H 5 were selected. The insulation of a film 24 mils thick was measured between test-plates having

an area of 56·8 sq. in. At 60° F. each oil was found to have a specific resistance of 6,000,000 megohms or over.

Oil of the H 1 type had, however, to have its temperature raised to 214° F. before its specific resistance had fallen to exactly 6,000,000 megohms, which was the maximum exact value determinable with the apparatus in use. The shape of the curve showing the effect of increasing temperature given in Fig. 29, shows that a further increment of 54° F. served to reduce the specific resistance to 600,000 megohms, and further indicates that initial values for specific resistance expressed as over 6,000,000 megohms may cover values many hundred times in excess of this. After heating the oil was allowed to cool; and the left-hand curve shows that even the short application of a temperature of 280° F. by producing a molecular regrouping of its constituents occasioned a lower specific resistance. At 100° F. the specific resistance was again exactly 6,000,000 megohms, and the oil would be well over this value at 60° F.

Oil of the type of H 3 on heating to 72° F. had then the maximum specific resistance exactly readable of 6,000,000 megohms, and on raising the temperature to 152° F. its value fell to 600,000 ohms. An increment of a further 100° F. reduced the value to 60,000 megohms. A very regular series of observations was made on the cooling curve indicating comparatively slight changes in the constitution of the oil, the value on cooling at 90° F. being 2,400,000 megohms or two-thirds the value on the heating curve (see Fig. 30).

Oil of the type H 5 gave a most irregular heating curve suggestive of the expulsion of moisture. These values being very irregular are not reproduced on Fig. 31, but the cooling curve, during which no molecular regrouping is likely to occur, is reproduced. It very closely resembles the cooling curve of type H 3. Taken on their heating curves alone, oil of the type H 1 has between the temperatures of 214° F. and 280° F. a negative temperature coefficient of about 1·4 per cent. per degree Fahrenheit, while oil of the type H 3 has between the temperature of 74° F. and 152° F. a negative temperature coefficient of about 1·15 per cent. per degree Fahrenheit, while from 152° F. to 252° F., the negative temperature coefficient is about 0·9 per cent. per degree Fahrenheit.

The general conclusions which can be deduced from this study point to the fact that the variation of specific resistance with temperature depends upon the grade of the oil, coupled with the suggestion that specific resistance measurements may be used to ascertain (by comparison of a series of heating and cooling curves, with a progressive increase in temperature), the point at which this obscure point of probable molecular regrouping of the hydro-carbon constituents takes place. This matter, while only perhaps of academic interest in regard to the classes of oils forming the purpose of this paper, may prove of value in the selection of oils for use on reciprocating engines using superheated steam.

APPENDIX I.

Note on Potential Gradient.

The strength of an electrostatic field is defined to be measured by the mechanical force, which would be exercised upon a unit electric charge placed in the field.

Or $F = qf$, where F is the mechanical force exerted on a charge of q units of electricity, placed in an electrostatic field of strength f.

The difference of potential between two points is defined to be measured by the work done in moving unit electric charge, from the one position to the other, against the electric forces. Let the points be taken near together, so that the strength of field may be considered constant over the short distance. Let f be the strength of field, then the force acting on unit charge placed in it will be f. The work done in moving this charge across the distance δx will be $\delta V = V_1 - V_2$, where V_1 and V_2 are the potentials at the points in question respectively.

Thus—

$$f \delta x = \delta V;$$

or—

$$f = \frac{\delta V}{\delta x};$$

or in the limit—

$$f = \frac{dV}{dx} = \text{the potential gradient.}$$

It is assumed, conventionally, that one Faraday tube or line of electrostatic force proceeds from each unit of electricity on a charged body. Imagine a point charge q in space, and surround it with a spherical surface, of radius r, of which the charge is the central point. Let f be the strength of field at the surface of the sphere, then $f = \frac{q}{r^2}$, or $r^2 = \frac{q}{f}$. The Faraday tubes will be symmetrically disposed about the electric charge, and therefore normal to the surface of the sphere. Consequently the density of Faraday tubes, where they cut the surface of the sphere $= D$

$$= \frac{q}{\text{surface of sphere}} = \frac{q}{4 \pi r^2}.$$

But—

$$r^2 = \frac{q}{f};$$

therefore—

$$D = \frac{q}{4\pi} \times \frac{f}{q} = \frac{f}{4\pi}.$$

From this reasoning it follows that potential gradient is proportional to the strength of the electrostatic field, or the density

of Faraday tubes, measured on an area at right angles to their direction.

N.B.—The introduction of the specific inductive capacity of the dielectric medium into these considerations does not alter this result.

APPENDIX II.

Since submitting the MS. of this paper to the Council the authors have had an opportunity of investigating an interesting case of the properties of the oil from a high-tension transformer after three years' use. The conditions were in every degree adverse. The transformer was frequently overloaded; on three occasions it had gone to earth

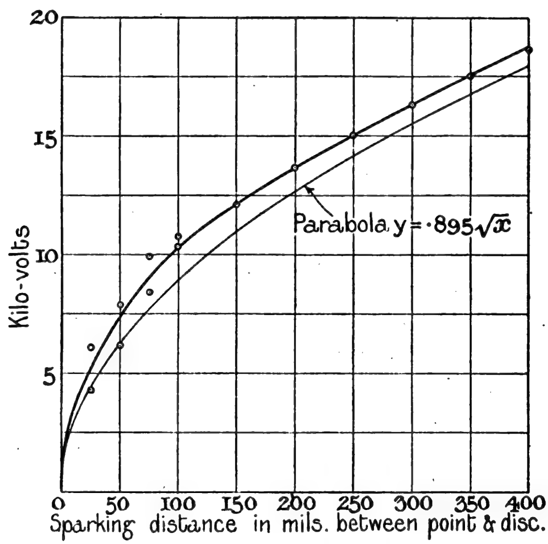

FIG. 32.

through failure of the fibrous insulation on the coils, it had been worked without its cover, and had stood in a corner of a Manchester machine shop. Dust and similar foreign matter had then free access to the oil. Of the grade of oil used, the works description was that it was mixed, and consisted of transformer oil purchased from two firms. The trade names indicated that these were of the classes designed as H 3 and H 5. Yet, after sedimentation, the dielectric strength curve of this oil was of an entirely normal character, as is indicated in Fig. 32.

The other properties were as follow :—

Viscosity	58·9.
Flash-point	177° C.
Specific gravity	0·8683.
Specific resistance	193,000 megohms.
Reaction	Slightly acid.
Resin	Small quantity.
Odour	Suggestive of ozone.

In conclusion, the authors have to express their indebtedness to a number of persons for the very valuable assistance which has been afforded to them. In the first place, their thanks are due to Mr. F. E. Pollard, F.I.C., F.C.S., who prepared the section on the physical and chemical examinations of oils for the authors, and who has carried out all the tests as to chemical properties mentioned in this paper. They are indebted to Messrs. Mather and Platt for permission to conduct tests on three different oils at their works; to Messrs. Eckstein Heap & Co. for the use of switchgear and apparatus; and to Messrs. Spencer, Huskinson, Ward, Turner, and E. Panter for laboratory assistance.

DISCUSSION.

Mr. C. J. BEAVER: As regards the general character of the oils taken by the authors as typical of switch and transformer oils, Figs. 2 to 7 and the table on page 172 give us a general idea of their electrical, physical, and chemical characteristics. If we arrange them in order of merit so far as the electrical and chemical properties are concerned, and in order of magnitude so far as the physical figures are concerned, we see that there is some rough relation between specific resistances and breakdown voltage, and between breakdown voltage and alkalinity or acidity, though not between breakdown voltage and resinoid contents; also that there is no relation between physical and electrical properties, H_3 and H_1 being the best of the series and almost equally good electrically, but quite different physically. While one expects some relation between specific resistance and dielectric strength, and also between dielectric strength and purity, I do not think that the impurities indicated in the table account for the wide differences between the various oils in specific resistance and dielectric strength. My own experience is that alkaline, acid, and resinoid substances are not the most usual kinds of impurity met with in mineral oils, but that moisture is by far the most predominant source of variations in electrical properties. It is practically impossible to dry an oil perfectly by the application of heat, and the elimination of the last traces of moisture from an oil will make far more difference to its electrical properties than will the removal of the alkaline, acid, or resinous substances such as are referred to in the table. In connection with this question of moisture, I think its elimination to the utmost practical Mr. Beaver.

Mr. Beaver. extent should not be one for the oil refiner or producer, but rather for the transformer and switch maker. There are such wide possibilities for the taking up of moisture in handling, packing, and transit that the variations in a single consignment of oil—referred to by the authors—are not surprising. Physical and chemical properties, which fix the general character of the oil, can be so easily adhered to by the oil manufacturer, and the elimination of moisture can be so easily ensured to a practically efficient extent, for instance, by filtration through beds of calcium chloride, that it seems to me reasonable to think that the oil user is in a better position to take care of its electrical properties than is the refiner. I am not suggesting that this question of moisture has been overlooked by the authors, but it hardly appears to have been given the prominence which, in my opinion and experience, it deserves. In view of the rare occurrence of alkalinity or acidity in mineral oils it would be interesting to know whether the authors have any theory as to the changes which they observed in studying the effect of disruptive tests on the chemical and physical properties of oils, where they found not only changes in degree of alkalinity after baking and testing, but also changes from slight acidity to marked alkalinity. The authors' experiments on the relation between dielectric strength and temperature are most interesting. The general trend of the curves for solid insulating materials is rather in the opposite direction to those shown for the various oils in Figs. 15 to 20. I am inclined to think that this striking difference between solid and liquid insulating materials is due to the much better dissipation of heat in the path of the stress in oils. The viscosity figures for these oils lend support to this view, and parallel cases will be familiar to those experienced in the testing of insulating materials. For the reasons I have just stated I cannot agree with the authors—and I think Mr. Peck will support me in this—that makers of oil-cooled transformers are wrong or misguided in applying lower test pressures to transformers when they are heated up at the end of a test run than after they have been allowed to cool. The dielectric which the transformer maker is testing is not the oil, but various solid or laminated dielectric materials, which have, to some extent at least, reverse electrical characteristics to those of oils at high temperatures. The relation of viscosity to temperature is a portion of the authors' subject on which a great deal of work has already been done, although almost entirely in connection with lubrication. The relation between fall of viscosity with temperature and electrical properties should prove exceedingly interesting, for the reason that, as I have demonstrated elsewhere, the general order of percentage decrease of viscosity with increase of temperature bears some relation to the surface tension of the oil, and the surface tension of the oil may be quite different in cases where oils of different origin give identical results under physical tests at the usual testing temperatures. In the detection of moisture, although the exsiccated cupric sulphate is very sensitive to the action of water, oil may be chemically dried, and improved electrically by such drying, beyond the point

when this test ceases to be sensitive. Without doubt the most delicate indication is the stream of hydrogen bubbles given off from a small piece of metallic sodium immersed in the oil, and as the nitro-prusside test for the detection of sulphur mentioned by the authors entails the use of metallic sodium there would appear to be little use for the dehydrated cupric sulphate. With regard to indicators, I find no necessity for testing the aqueous extract while hot, and do not personally prefer tincture of cochineal to the more usual phenol-phthalein and methyl-orange. I have always found phenol-phthalein reliable, and do not understand the statement that it is not affected by the soaps of alkaline metals. I have some doubt as to the identity of the resinous bodies to which the authors frequently refer in connection with their type samples, and should like to know whether they have been isolated as such, or identified by such a test as the Liebermann-Storch test. Mr. Beaver.

Mr. J. S. PECK: From a practical point of view there are three necessary qualities in oil used for transformers: (*a*) high fire test; (*b*) high dielectric strength; (*c*) freedom from deposit under working conditions. The authors have dealt with (*a*) and (*b*), but have not touched upon the question of deposit at all, and I hope they will extend their investigations to cover this question, for while there are a number of oils on the market which are quite satisfactory as regards fire test and dielectric strength, it is very difficult to obtain oil which does not throw down a deposit when worked at a comparatively high temperature. High dielectric strength is largely a matter of purity, while the method of obtaining a high flash-point is well understood, but regarding the question of deposit, very little appears to be known beyond the fact that some oils exhibit it to a marked degree, while others are practically free from it. It may be said to be the most important question now before the manufacturers and users of oils for insulating purposes. There is no use in purchasing expensive oil of great purity, unless precautions are taken to keep the oil in this condition during shipment. Oil will absorb a certain amount of moisture if exposed to a damp atmosphere, and when shipped in wooden barrels there is always a risk that if it is stored out of doors water may work in through the heads of the barrels. On this account the use of wooden barrels for shipping and storing oil has been largely done away with. The authors have devoted considerable space to the question of the specific resistance of oil, but I do not think the question of specific resistance is one of any practical importance, unless it forms some indication of the dielectric strength of the oil, and from the results obtained this is apparently not the case. It is a very interesting fact that the dielectric strength of oil appears to increase very rapidly with the temperature, whilst the specific resistance decreases at an even greater rate. It would be interesting to know what would happen if the curves on page 199 were repeated several times. I agree with the remarks of Mr. Beaver, and therefore disagree with the authors, in regard to their statement that a transformer should not be tested with Mr. Peck.

Mr. Peck. a higher voltage when cold than when hot, because the oil has little to do with the insulation strength, except as preventing surface discharges. Breakdowns usually occur through the solid dielectric, and there is no doubt that this is weaker when hot than when cold. I presume that the arcing effects were all obtained by breaking alternating current below the surface of the oil. It would be interesting to compare the effect of the alternating-current arcs with direct-current arcs, as experience indicates that the carbonising effect is very much greater with direct current than with alternating.

Mr. Southcombe. Mr. J. E. SOUTHCOMBE : Speaking as a chemist, with some experience of oil investigation, I cannot quite agree with some of the points raised by the authors as to the purity of the samples. In the first place, an examination of many samples of transformer and switch oils has not revealed the universal presence of alkali which the authors appear to have observed. It is, in fact, an extremely rare thing nowadays to find alkali in oil of this type, and I can only say that if an oil submitted to me for adjudication contained any traces of this substance I would reject it at once as totally unworthy of any further consideration. The authors have apparently had somewhat abnormal samples under consideration. With regard to the question of moisture, the authors state that they have found oils containing as much as 0·57 per cent. of moisture, but it would appear that they had estimated this by drying at 100° C. and noting the loss. This would not be a reliable method, since the losses from volatilisation of the oil would always be an unknown quantity, and would totally vitiate the figures. There appears to be some haziness as to the amount of moisture contained in oils. I have conducted a long series of experiments on this matter from several points of view. Oil and water are immiscible, and if an oil contains water at all, it is present in fine globules distributed throughout the mass. Now if the globules were big, the water would quickly settle out of the oil, while if they were very fine indeed they might be retained for long periods, since the mixture would partake of the properties of an emulsion. Now if the globules be very minute, there would have to be an immense number of them present to have anything like ½ per cent. of water in the oil; consequently the water surfaces would be great, causing considerable thickening, and the oil would be very turbid. It is inconceivable that any self-respecting oil manufacturer would submit such an emulsion for transformers, but the burning question is the influence of very minute traces of moisture on insulating properties. An oil may be quite bright and yet contain absorbed moisture, but such moisture is present only to the extent of 0·1 per cent. or less. The quantitative estimation of such minute traces chemically is almost impossible, but the dielectric strength is a very delicate test. In my opinion variations in dielectric strength can be correlated very largely with these exceedingly minute traces of moisture, which have a far greater influence on the electrical properties than any so-called chemical impurity in well-refined oil of standard quality. There is very little evidence to show that disruptive discharge proceeds

more readily in the presence of resins, etc. In fact, resin oils (containing almost wholly resins) are admirable insulators. A study of the figures given in the authors' paper shows that what they called resin-oil content does not explain the variations in dielectric strength. I would like to emphasise again that in my opinion it is not chemical impurities (in the majority of cases) but exceedingly minute traces of moisture, that are the cause of many discrepancies in dielectric strength. Mr. Southcombe.

The problem how to get rid of this moisture resolves itself very much into a commercial question. Is it to be done by the oil manufacturer or by the transformer builder? No doubt the oil manufacturer can supply a perfectly anhydrous fluid, but not if the electrician asks for an oil at a price which his better sense must tell him will make it impossible to devote much attention to these minute but important details. Considerable success has attended drying the oil by electrical resistances immersed in the oil, but it would appear to me a better investment to pay the experienced oil manufacturer his price and demand from him an anhydrous oil. Although the question of chemical impurities does not appear so important as moisture in lowering the dielectric strength, yet it is absolutely imperative that an oil should be of the highest possible purity, since the influence of acid, and even more that of alkali, on the windings is disastrous, while at the same time any tendency for the oil to resinify or oxidise on heating will materially affect its heat disseminating powers. In addition to the points mentioned, no specification would be complete which did not demand tests as to the durability of the oil on successive heating and cooling. On the electrical tests I cannot speak with authority, but some experiments made by Mr. Lustgarten at the Manchester School of Technology. and the conclusions of Russell do not confirm the authors' results at such short distances. Further, the carbon produced by the passage of the arc requires some considerable time to settle, and a sufficient interval must elapse before making a second puncture. The carbon produced is disseminated throughout the oil in a kind of semi-colloidal suspension of charged particles, which settle at varying rates in different oils. I am at present investigating this phenomenon and have obtained some most interesting results, which have their practical application in the design of oil switches.

Mr. J. LUSTGARTEN: I must congratulate the authors on having placed on record the physical and chemical properties of this important insulating material before and after heating and disruption. Of the properties mentioned on page 167 as requisites in a mineral oil, one might add that evaporation must be small, and that no trace of sediment after repeated heating and cooling should occur. The authors mentioned that resinoid matters contaminate oil when stored in wooden barrels. I would like to ask the authors if the wooden barrels which are sent into this country from America are made of oak, because if so I hardly see that resinoid matters would be likely to get into the oils with such construction of the barrels. As the Mr. Lustgarten.

Mr. Lustgarten.

authors recommend standardised methods of testing, though (on page 166) they deprecate criticism of methods of taking the dielectric test, it must be stated that the sparking voltage depends on many factors which the authors have not mentioned. These factors are : (*a*) The width of the glass vessel in relation to the spark distance and the size of the electrodes ; (*b*) the position (depth) of the spark-gap in the oil ; (*c*) the amplitude factor of the machine used ; (*d*) the rate of growth of the testing pressure ; (*e*) whether the electrodes are insulated or grounded ; (*f*) the shape of the electrodes. The amplitude factor is important, because if the machine has a peaky wave the oil will break down very much earlier. Earthing one electrode alters the maximum potential gradient on the insulated electrode. With regard to (*d*) a modification of the method is to move the electrodes keeping the testing pressure constant. With regard to the shape of electrodes, I cannot see why the authors get the voltage distance curve for ¾ in. diameter spheres to lie below that of needle-points, for we know that in the air the voltage distance curve lies above that of needle-points. In my own results on oils, the larger sized spheres give curves lying above the smaller size, and obviously the needle-point is a very small sphere, and for a given sparking distance and voltage the potential gradient is steeper with needle-points. I have experimented with ½ in., ¾ in., and 1 in. spheres, and have found best results obtained with larger spheres than with the smaller ones, but the distances must be greater than ⅛ in. With regard to the curves for spheres, these bend over as in the needle-point curve. Dr. Russell in a very excellent paper given some years ago suggested that the best way of expressing the dielectric strength of an insulating material is by the maximum potential gradient at breakdown. This for parallel plates, electrodes immersed in the dielectric, would be $\frac{v}{x}$, but for spheres $\frac{x}{v} f$, where $v =$ maximum voltage, $x =$ spark-gap distance, f a factor depending on x and the diameter of the sphere. (Here we see the influence of the amplitude factor on v and hence on the potential gradient.) The dielectric strength of the best oils is about 160 kilovolts per centimetre, medium oils about 100. The potential gradient for the oil in the curve on page 177 is rather low—80 kilovolts per centimetre. The authors remark that the dielectric strength improves with flashing over, and is due to traces of moisture and impurities being burned out. This was particularly apparent in an oil submitted to me to test. The breakdown voltage went up from 42 to 80 kilovolts (R.M.S.) in twenty days with a test taken once every twenty-four hours, but after repeated breakdowns the strength diminished—80, 71·2, and 63·6 kilovolts being readings taken on three consecutive days. I must mention that in testing oil sufficient time should be given to allow air bubbles to rise, and finely divided floating or colloidal matter to settle, as they will seriously affect the results, especially at the small sparking distances. In a particular case the breakdown voltage a few minutes

after pouring in was 10 kilovolts, half an hour afterwards 17 kilovolts, and twenty-four hours later 48 kilovolts. (In the latter test traces of moisture must also have been removed.) The authors find (page 186) that the dielectric strength of the oil increases with temperature. This result seems the reverse of what we might expect. In solids it is the reverse. Did the authors find this to hold after repeated heating and cooling of one specimen in order to eliminate traces of moisture and impurities? For drying oils, I have found that hot air and sodium answer very well. In one case a transformer oil treated with sodium increased in strength from 107 to 122 kilovolts per centimetre. Mr. Lustgarten.

Mr. D. B. MELLIS (*in reply*): Replying to Mr. Beaver, the purpose of recording, besides the observed physical behaviour of the oils examined, the result of their chemical examination, was not to infer that the physical properties found were due to chemical impurities. Had no chemical examination of the oils been made, it would always have been open to any one to say that variations in the behaviour of the oils under discussion were due to variations in their degree of purity. The slight variations in the reaction of oils observed, after testing for dielectric strength, may be due to several causes. For instance, electrolytic action may change some of the impurities from acid to alkali or *vice versâ*. Or again, owing to the high voltages used, the air surrounding the testing vessel and in contact with the oil becomes ozonised, and nitrous oxide is also formed. These substances may easily affect the reaction of so nearly neutral a liquid as the oil usually is. Mr. Beaver appears to think that it is asking too much of the oil people to expect them to supply oil up to a standard of specific resistance, but in our opinion the specific resistance test is really a very delicate test for the chemical purity of the oil in question. In fact, no oil having a relatively large amount of water, or other harmful impurity, will have a high resistance. This is borne out by the set of oils tested, viz., H 1 to H 6. The two oils with the highest resistance were the ones of greatest purity, and gave the most consistent results in all the other tests. Notice how closely the heating and cooling curves for these oils agree when tested for dielectric strength at different temperatures. As regards the reasonableness of expecting the oil refiners to work to a standard of specific resistance, we would point out that the standard of chemical purity exacted from copper refiners is specified by the specific resistance of the copper which must be obtained. If the copper suppliers can work to such a specification we cannot see anything unreasonable in asking the oil suppliers to work to a similar one. Mr. Beaver remarks that we do not attach sufficient importance to the presence or absence of water. This is unintentional. The question of drying oil is of great importance, whether undertaken by the oil refiner or by the user. It is of the utmost importance for the refiner to supply absolutely dry oil, but it is of no use for him to do so unless the necessary care is taken to keep it dry. When the user has to dry his own oil we should suggest warming it up in a vacuum Mr. Mellis.

Mr. Mellis. oven to a moderature temperature. Too high a temperature must not be employed or the nature of the oil may be changed, as is proved by the temperature resistance curves (Figs. 29 and 31). If possible, when the oil is in the vacuum oven, dry air should be allowed to bubble through it, so as to stir it up and help the evaporation; and we would remark by "dry air" we do not simply mean "hot air," but air which has been freed from water by passing it over calcium chloride, or, better still, phosphorus pentoxide.

The method suggested by Mr. Southcombe of stirring the oil with a cage containing metallic sodium would appear to have the disadvantage that caustic soda would tend to replace the previous water, and would afterwards attract to itself much more water, unless the vessel were hermetically sealed after treatment of the oil.

Mr. Beaver remarks that the other physical properties, such as viscosity and flash-point, do not appear to have any relation to the electrical properties of an oil, and in this connection we should like to remark that a sample of ordinary illuminating paraffin oil bought at a very cheap rate gave a curve of dielectric strength at least twice as good as the best transformer oil, and, needless to say, both its viscosity and flash point were very low, far lower than those of any transformer oil. It is also interesting to note that the dielectric strength of any transformer oil increases with rise in temperature (see Figs. 15 to 20), while its viscosity falls (see Fig. 21). This relation between viscosity and dielectric strength may be accidental, both being due to some molecular condition, of which we have no knowledge. We have referred the chemical points to Mr. F. E. Pollard; and, having considered his reply, we quite agree with Mr. Beaver that variations in electrical properties may be caused to a great extent by very small proportions of moisture; but the question of alkalinity is of importance because a very slight trace of alkali tends to cause absorption of moisture. We are not in favour of filtration through calcium chloride for drying oils, but prefer Mr. Peck's vacuum oven process. Another good method of eliminating moisture is by blowing hot dry air through the oil. We have not, however, had an opportunity of carrying out this process on the commercial scale. We find that the exsiccated cupric sulphate test is sufficiently sensitive, when suitably applied, by packing about 1 cm. of the stem of a funnel with small fragments of pumice, charged with the anhydrous sulphate, thoroughly drying, and then allowing a sufficient quantity of oil to percolate slowly through the pumice. At the same time we endorse Mr. Beaver's remarks as to the sodium test. With regard to indicators, we do not advise the testing of the aqueous extract whilst hot; but cochineal has the advantage that it can be used for hot liquids, whilst methyl-orange cannot; and moreover the colour change of methyl-orange, with traces of alkali, is not easily observed, unless the indicator be first made feebly acid and then carefully neutralised. It seems to be generally taken for granted that the alkali in oil invariably exists as hydroxide. This is very far from being the case, and consequently

when phenol-phthalein is used as an indicator considerable traces of alkali escape detection. Mr. Beaver says that he does not understand the statement that phenol-phthalein is not affected by the soaps of the alkali metals. The neutrality of phenol-phthalein to soaps permits its use, in soap analyses, for the estimation of free caustic alkali, whilst the subsequent volume of acid required to give neutrality, in the same solution, with methyl-orange is a measure of the alkali combined with fatty acids, etc., but not of carbonates, silicates, borates, etc., which are insoluble in alcohol. However, soaps of the alkali metals are very seldom found in mineral oils of the type under consideration, although aluminum soap is by no means infrequently met with. The exact nature of the "resinoid" matter was not determined. In most cases it appeared to be tolerably pure resin; but in several instances examination revealed admixture of other substances, hence the employment of the term "resinoid matter" instead of "resin." Mr. Mellis.

With regard to Mr. Southcombe's statement that it was an extremely rare thing nowadays to find alkali in oil of this type, out of considerably more than 100 samples examined during the last eighteen months or so, at least 80 per cent. have been found to contain alkali, sometimes in slight, sometimes in very distinct traces; but had phenol-phthalein been used as an indicator, no doubt practically the whole of these would have been returned as neutral. Comparative tests have demonstrated that cochineal and methyl-orange are more than ten times as sensitive to alkaline carbonate as phenol-phthalein. Whereas the addition of 0·03 c.c. of a solution of sodium carbonate containing one part in 1,000 to about 10 c.c. of water containing the indicator gave a sharp and distinct reaction with both cochineal and methyl-orange, no less than 0·4 c.c. of the same alkaline solution added to the same volume of water containing phenol-phthalein was required to give a colouration. From this it is apparent that the aqueous extract from an oil might contain a weighable quantity of alkali and yet be quite neutral to phenol-phthalein. Mr. Southcombe criticises at some length the methods employed by us in making chemical examination of oils. Some of the points raised by him are dealt with above. With regard to his remark that he has very seldom found oils to have an alkaline reaction, but has generally found them to be acid, in our experience this is not borne out. We may say that all the samples were obtained from well-known makers of transformer oil, who all supply large quantities of such oil. They cannot therefore be considered to be abnormal samples, as Mr. Southcombe suggests. Of all the oils discussed in this paper only one showed an acid reaction, viz. H 5, all the others being neutral or alkaline in spite of any treatment they had undergone, with the single exception of H 4, which showed an acid reaction after baking, but at no other time. In reply to the objection that the loss of 100° C. would not give any measure of the moisture, a reference to the section on chemical examination, page 183, will make it clear that the authors had no intention of suggesting that

Mr. Mellis. it would do more than give the amount of moisture, plus oils of low boiling-point. The omission of "etc." after the word moisture on page 167 is to be regretted. With reference to Mr. Southcombe's criticism of our method of making tests for dielectric strength, in which he quotes Russell as saying that such determinations are not reliable when tests are made over short distances, and that consequently high voltages must be employed, we would point out that when Russell made this statement he was discussing the experiments of Hobbs, who tested over microscopic distances down to 3×10^{-7} cm., and he goes on to say that it is not safe to calculate dielectric strengths from the observed disruptive voltages, when the electrodes are less than 1 mm. apart, and suggests that, for accurate work, at least $\frac{1}{2}$ cm. should be tested over. Now, as the distances we tested over range from about $\frac{1}{2}$ mm. up to over 1 cm., we do not suppose that Russell would take exception to the lowness of the voltages we used. We may also say that our results are in accordance with Russell's statement, in that we generally obtained more consistent readings with the higher voltages than with the lower ones. Mr. Southcombe's tests were apparently mostly made using balls as the electrodes, and in his case air bubbles would be more likely to give trouble than in our case, where the upper electrode was always a needle, giving little opportunity for air bubbles to cling to it, and so produce erratic results. Mr. Peck emphasises the necessity of oil for switch and transformer work having a high dielectric strength, and also freedom from deposit, and discusses what this latter is due to. One usual explanation offered is that varnish, supposed to be oil resisting and used in transformer insulation, is not actually so, and that it disolves out, or partially dissolves out, forming a more or less gelatinous solution, which by electrostatic attraction clings to the windings, and impedes the free circulation of the oil. This, however, does not appear to cover every case observed, and we are forced to suppose that the thickening, in some cases at least, is due to polymerisation of some of the hydrocarbons of which the oil consists, or even to chemical change, brought about by repeated heatings and coolings. This is a question for chemists rather than electrical engineers. In this connection it is interesting to remark that there is at least one insulating varnish on the market whose makers claim that its hardening, or conversion from the liquid to the solid state, is due to polymerisation brought about by the baking process, and it may very well be that a similar action takes place in oils. We fully agree with Mr. Peck in his remarks about carelessness in handling oil sent out in casks, so that it becomes contaminated with water, and consider that for electrical work nothing but hermetically sealed metal drums should be permitted for containing the oil. While agreeing with Mr. Peck that high dielectric strength is a most important feature, we still think that a high resistance is of some value, as the latter is only obtained with very pure oils, and may be taken as a measure of their chemical purity. The specific resistance temperature curves, Figs. 29 to 30, were taken by using a fresh sample of the oil in question as

supplied by the makers, and testing for specific resistance with first a rising temperature and then a falling one. It would be interesting to take the oil through a repeated cycle of temperatures, noticing its specific resistance changes all the time. With regard to the suggestion thrown out in the paper that it might be safer to test transformers with a higher voltage when hot than when cold, on account of the increase of dielectric strength of oil with rise in temperature, Mr. Peck disagrees on the ground that oil is not the principal insulating medium, but merely the cooler. This criticism, of course, would not hold good in the case of a transformer so designed that the oil was the principal insulator. Referring to the much greater relative amount of carbonisation which takes place in the oil tanks of direct-current controllers or switches than in the tanks of those controlling alternating current, we would point out that the fact of the alternating current passing through zero twice per cycle gives the oil a very much better opportunity of extinguishing the arc in the latter than in the former case, and also that, from the very nature of alternating currents, no great self-induction can be produced in the circuit, otherwise the electromotive force would not be able to propel the current through it, so that in the case of alternating current no "highly inductive arcs" have to be quenched, which is often the case with direct current. Mr. Mellis.

Replying to Mr. Lustgarten, we understand that when American oil is shipped in barrels they are usually made of oak, but in the case of Russian oil steel drums are generally used.

The glass containing vessel of the apparatus illustrated in Fig. 8 is about 2 in. in diameter, and as the electrodes are placed axially it is obvious that the distortion of the electrostatic field due to the high specific inductive capacity of the neighbouring glass would have no effect on the field between the two electrodes, which were never separated by more than 0·4 in. The curve of voltage of the alternator used did not differ very much from a true sine curve, but was distinctly flatter at the top. The amplitude factor has not been calculated, but it cannot be far removed from that for a sine curve. The value in kilovolts given on the curves of dielectric strength is expressed in virtual volts (R.M.S. value), so that the maximum volts applied would be about 1·4 times the values given. We would also add that not only the maximum voltage applied decides the limiting sparking distance, but also the length of time during which the voltage is applied. There appears to be a time lag, so that a given gap will stand for a very short time a voltage which would ultimately break it down were it applied continuously. From this we should conclude that with a higher frequency higher dielectric strength would be obtained than by using a lower frequency. This deduction is borne out by the figures given on page 178, which show the breakdown voltage over a fixed gap at two frequencies. Neither of the electrodes was earthed, but as everything was very well insulated, and the voltages used were never higher than about 25,000, we do not suppose that earthing would have made much difference. Referring to the curves given in Fig. 11, Mr. Lustgarten

Mr. Mellis. does not understand why the curve obtained when testing between balls at any point comes below the curves obtained in testing between points, and states that in his experiments in air this is not the case. We would put forward two suggestions in this connection. When breakdown occurs in air or other gas, the physical process consists of the manufacture of ions by the strong electrostatic field to such an extent that finally the conductivity of the air is so increased that a violent discharge takes place through it. The mobility of the gaseous ions will undoubtedly assist this action. In a liquid, however, the ions will be, relatively speaking, stationary. Consequently it would not be safe to argue as to the phenomena of breakdown in one medium from experimental results obtained in the other medium. Further, J. J. Thomson shows that when ions are present the electrostatic field is distorted, and cannot be calculated from the geometry of the electrodes only. It is obvious, therefore, that if in the one case the ions can freely move about, and in the other they are relatively stationary, the distribution of the electrostatic field will be different in the two cases, and we may expect the phenomena of breakdown to differ. The other suggestion we would put forward is that, when testing with one or both the electrodes pointed, only a very small volume of the oil is subjected to intense dielectric stress, whereas when testing between balls a very much greater volume of oil will be stressed. Owing to the fact that the oil is probably far from homogeneous, there will be a much greater likelihood of a weak part being stressed and broken down in the latter than in the former case. In a similar way it would not be safe to estimate the dielectric strength of a mile of cable as equal to the value experimentally found for a yard length, as there would be 1,760 chances to 1 of a weak point being included. Mr. Lustgarten has not experienced erratic readings when testing between spheres, but we have. It was on account of obtaining very much better sets of readings with needles that we finally adopted them. The curves on Fig. 11 exhibit these statements very well. The lower full-line curve, obtained when testing between a point and disc, passes through nearly all the experimental readings, which are indicated by circles, whereas the points obtained when testing between balls, indicated by small squares, do not follow any exact law. The only advantage that we can see in testing between balls is that the absolute value of the physical constant "dielectric strength" can be more readily calculated than when two points or a point and disc are used, and as in our hands the latter gives the more regular results, it is the more suitable for determining the relative dielectric strengths of oils, all of which are subjected in turn to identical conditions. Mr. Lustgarten also says that had we tested with higher voltages between spheres we should have found that the curve connecting sparking voltage and distance between electrodes was not linear, but bends over. We would point out that we do not state that this curve is linear, the words used in the paper being, "From this we should expect that the curve connecting puncturing voltage and distance will be nearly a straight line when testing

Mr. Mellis.

between balls whose diameter is considerable as compared with the distance tested over." Further, the reasoning which led to this result, if extended to distances great as compared with the diameter of the balls used, would lead one to expect that the curve would bend over in a similar manner to the curve obtained when testing between a point and disc. Mr. Lustgarten remarks that the sample of oil experimented with in Fig. 11 is not very good, and that much higher figures can be obtained. This we do not doubt. The sample in question is an ordinary commercial sample, not treated specially in any way, but fairly representative of what will be obtained in the market. Of the oils designated by the letters H 1 to H 7 all were ordinary commercial samples, none being appreciably better nor worse in their purity than those supplied in bulk to large purchasers. At the commencement of our paper we referred to the splendid curve of high dielectric strength, widely circulated, but rarely attained in practice. We therefore urge that in dealing with commercial oils actually supplied our researches have tended towards practical utility, which must be the chief consideration of the purchaser.

RATING AND TESTING OF MOTORS FOR INTERMITTENT WORKING.

By Dr. ROBERT POHL, Associate Member.

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Introduction.—According to the usual classification we may distinguish between three groups of electric motors, those for continuous working, for short-period working, and for intermittent working.

The distinction between the two latter classes is as follows :—

A machine for short-period working is supposed to have a running time not sufficient for the final temperature to be approached, succeeded by a standing time long enough to allow of its cooling down again practically to the temperature of the atmosphere. A motor for intermittent working, however, is subjected to alternate periods of work and rest, both of short duration, so that its temperature rises to a practically constant value.

This paper is devoted exclusively to the last of the above classes, comprising a large number of machines for different purposes, such as crane, hoist, lift, and traction work. It deals more particularly with suitable methods of testing and rating the same. This subject is an important one, considering the very unsatisfactory character of the testing practice at present prevailing, and in view of the need for definite and generally accepted regulations on the rating and testing of electrical machines.

The guiding principle in the testing of any finished machine is that the test conditions imposed on it should represent, as accurately as possible, its future working conditions. There are cases, however, in which it is exceedingly difficult or altogether impossible to reproduce these conditions on the test-bed of the manufacturer. A compromise becomes unavoidable, consisting in the adoption of such tests as can be imposed without excessive difficulty, and which allow of sufficient conclusions being drawn from them as to the normal behaviour of the machine.

The motors forming the subject of this paper are, perhaps, the most conspicuous examples within the realm of electrical engineering. As it is impossible to reproduce the working conditions, they are, by almost universal practice, subjected to a short time run for the purpose of ascertaining their temperature rise. The duration of the test is usually half an hour, except in the case of traction and haulage motors, which are tested for one hour or a longer period.

Whenever a test conventionally imposed is different in character from the real working conditions there is, however, a twofold danger.

Firstly, the purchaser may not be aware of the relationship between the conventional test and the particular working conditions for which the machine is required. In consequence he may obtain a motor either too large and expensive, or of insufficient capacity.

Secondly, the manufacturer may favour designs and constructions which improve the performance during the specified test, though not necessarily under working conditions, at the disadvantage of such real improvements which the traditional tests would not reveal.

The aim of this paper is, first of all, a negative one—viz., to prove that the prevailing practice of testing intermittently working motors is open to serious objections from both these points of view. On this account the proposal will be made to abandon short time tests completely. It will then be suggested to adopt in their place methods of testing machines for intermittent working, which will be shown to be more suitable.

To prove the misleading character of results obtained on short time tests we have to consider the relation of the temperature rise after a short time run on full load to that obtained when running intermittently with a definite load factor. E. Oelschläger,* R. Goldschmidt,† C. W. Hill,‡ and others have fully dealt with this subject, but it will be well for us to go briefly over the same ground again in a somewhat different manner.

Load Factor.—It is assumed throughout this paper that the duty of the motor is known beforehand, or where this is not the case, that a definite cycle of operations can be adopted with which the motor should be capable of dealing. According to the usual definition, the load factor f is given by the expression—

$$f = \frac{t'}{t' + t''} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where t' = time of running, t'' = time of rest, $t' + t''$ = duration of total period. This simple definition is based on the assumption that the motor when running is always exerting exactly its full power (see curve A of Fig 1), which leads to the important relation—

$$f = \frac{\text{mean loss under working conditions}}{\text{loss at full load}} = \frac{W_m}{W} \quad . \quad . \quad . \quad (2)$$

The above assumption is inadmissible, because in practice the load curve is invariably of a much more complex shape, such, for example,

* *Elektrotechnische Zeitschrift*, vol. 21, p. 1058, 1900.
† *Journal of the Institution of Electrical Engineers*, vol. 34, p. 660, 1905.
‡ Ibid., vol. 36, p. 290, 1906.

as curve B, Fig. 1. We must free ourselves from it by adopting a more general definition of the load factor f, applicable to any shape of the load curve. In doing so, let us keep in mind that it is desirable to maintain the important connection between f and the mean loss as stated in (2). With this end in view, and considering that the losses are practically proportional to the square of the load, we define—

$$\text{Load factor } f = \frac{(\text{virtual current})^2}{(\text{full-load current})^2} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

The virtual or effective current is the R.M.S. value of the load curve in amperes. It may be calculated from a diagram of operations and subsequently verified by means of a registering ammeter. The distinction between the external and the internal load factor as introduced by C. W. Hill* is thus avoided. In determining the load factor, due account should be taken of the heavy starting currents which are often

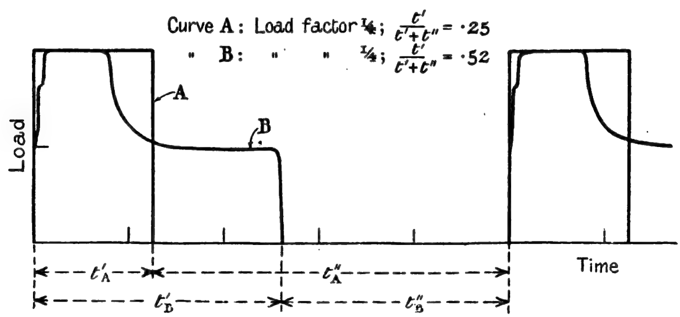

FIG. 1.

met with in practice, and which, as Claude Hill has shown, may have a great bearing on the temperature rise. In connection with shunt-wound crane motors, it will, of course, be kept in mind that the duty of the field coils may in certain cases be higher than that of the armature.

Temperature Rise under Working Conditions.—A motor working with a definite load factor will have a temperature curve as shown in Fig. 2, consisting of parts from the heating and cooling curves. We have to distinguish between r, R, r_i, and R_i the momentary and final values of the heating curves for continuous and intermittent running respectively. R_i is the final mean value as indicated in Fig. 2, which is somewhat smaller than the final peak value $R_{i\ max.}$. In nearly all practical cases, however, the difference is negligible on account of the short duration of the running period, and we are justified in confining ourselves to the consideration of R_i.

* *Journal of the Institution of Electrical Engineers*, vol. 36, p. 304, 1906.

A continuously running motor has reached its final temperature when the rate of heat dissipation is equal to the rate of heat generation. Hence $R b = W$, or—

$$R = \frac{W}{b} \qquad (4)$$

where $b =$ watts dissipated per degree temperature rise.

An intermittently running motor will similarly have a final temperature rise—

$$R_i = \frac{W_m}{b} \qquad (5)$$

provided that the rate of cooling, *i.e.*, the value of b, is the same whether the motor be running or standing. This is not correct for machines of the ventilated type, which will be considered later on, but we may take

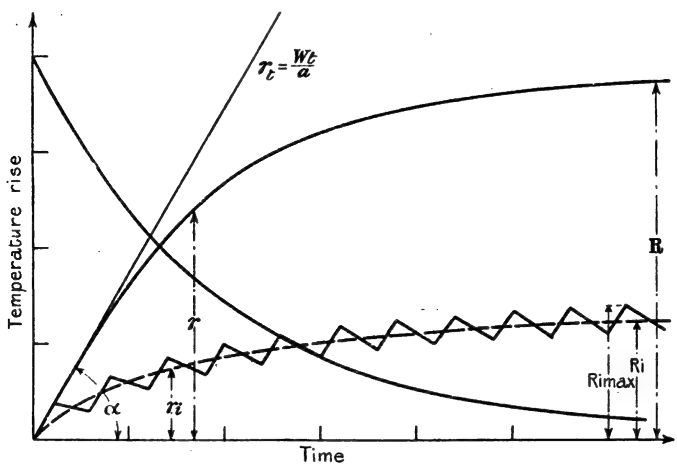

FIG. 2.

it that it applies approximately to totally enclosed machines.* As it is with these that we wish to deal at present, we may take equation (5) as being applicable.

Now, from the definition of the load factor—

$$W_m = W \times f,$$

hence—

$$R_i = \frac{W \times f}{b} = R \times f \qquad (6)$$

* Belt-driven totally enclosed machines show frequently a much lower rate of cooling when standing than when running. This is largely due to the ventilating effect of the pulley and belt, and sometimes to circulation of air through small openings in the casing.

The final temperature rise of a totally enclosed motor for intermittent running is equal to that it would obtain when working continuously multiplied by the load factor. It also appears (and this is an important point) that the final temperature rise of a motor, whether used for continuous or intermittent working, depends for a given loss entirely on its heat-dissipating qualities, *i.e.*, chiefly on the amount and character of its cooling surface.

In practice the temperature of a machine is not uniform, but differs in different parts. The letters r, R, r_i, R_i, must therefore be understood to refer to the temperature rise of the hottest accessible part, which is the limiting factor for the rating. Accordingly we must define b as the watts dissipated from the surface of the whole motor per degree temperature rise of the hottest accessible part.

This leads to the equation—

$$b = \text{cooling surface} \times \text{mean specific dissipation} \times \frac{\text{mean temperature rise of surface}}{\text{temperature rise of hottest accessible part}} \quad . \quad . \quad . \quad (7)$$

where mean specific dissipation = average number of watts dissipated by unit of surface per degree temperature rise of surface.

Having now clearly recognised the factors determining the temperature rise under working conditions, let us similarly consider the temperature rise under test conditions.

The Temperature Rise after a Short Time Run.—This will be found for any desired length of run t, if we know the equation of the heating curve $r = \phi(t)$ (Fig. 2). According to E. Elschlager, this is an exponential curve of the form—

$$r = \mathrm{R}\left(1 - e^{-\frac{t}{\mathrm{T}}}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

where—

e = basis of natural log = 2·718,
T = time constant of the motor (in hours).
t = length of run (in hours).

It will not be out of place to consider the proof of this statement in order to be conversant with the assumptions underlying it and to find out the meaning of T.

The assumption is made that the heated body is homogeneous, and that a constant amount of heat per unit of time in watts is generated in it uniformly throughout the body. Supposing no dissipation took place, so that the whole of the energy produced had to be stored in the form of heat energy, the temperature of the body would rise according to the straight line—

$$r_t = \frac{\mathrm{W}\,t}{a} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

where a = watt-hours stored per degree temperature rise (Fig. 2).

The gradient of this hypothetical line—

$$\frac{r_t}{t} = \tan \alpha = \frac{W}{a} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

must correspond to the gradient of the actual temperature curve at the commencement ($r = 0$), when there is as yet no dissipation of heat due to radiation, etc. With increasing dissipation, however, the rate of increase in stored energy, and therefore the gradient of the r curve, will decline more and more from its initial value, and generally the gradient will be—

$$\frac{d\,r}{d\,t} = \frac{W - W'}{a} = \frac{W - b\,r}{a} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

where $W' = b\,r$ is the amount of heat dissipated at the respective temperature expressed in watts. This differential equation leads immediately to—

$$r = \frac{W}{b}\left(1 - e^{-\frac{b\,t}{a}}\right) = R\left(1 - e^{-\frac{b\,t}{a}}\right) = R\left(1 - e^{-\frac{t}{T}}\right),$$

where—

$$T = \frac{a}{b} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

Equation (8) will give us the temperature rise after a run of t hours, whilst (12) states the meaning of the time constant T.

For the consideration of half-hour tests, however, with which we have mostly to deal in practice, we may greatly simplify the result. On looking into the temperature curve of any machine excepting the very smallest sizes, we observe that after half an hour's run the temperature has departed only very little from the straight line $r_t = \frac{W \times t}{a}$.

Taking further into account that the exponential curve is after all only an approximation, because it is based on suppositions not strictly correct, we are justified for further considerations in replacing the exponential curve by the straight line—

$$r_t = \frac{W\,t}{a} \text{ for } t \leqq \tfrac{1}{2} \text{ hour.}$$

Hence for half-hour tests—

$$r_{\frac{1}{2}} = \frac{W}{2\,a} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

and for quarter-hour tests—

$$r_{\frac{1}{4}} = \frac{W}{4\,a} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

For practical purposes we must again define r as the temperature rise of the hottest accessible part. The constant a represents, therefore, the watt-hours stored in the whole machine per degree temperature rise of the hottest accessible part, and may be written—

$$a = \text{weight} \times \text{mean specific heat} \times \text{heat distribution factor} \quad . \quad (15)$$

where the heat distribution factor is the ratio—

$$\frac{\text{mean temperature rise of mass}}{\text{temperature rise of hottest accessible part}},$$

which prevails after the time t.

Whilst the final temperature rise of an intermittently running motor with given loss depends on the factor b—equation (7)—we now find that the rise after a short full-load run depends on the factor a, and that the latter consists of constituent parts altogether different in character from those forming b. The temperature rise under working conditions is determined by the heat-dissipating properties—*i.e.*, mainly the surface; that under conditions by the heat storing properties—*i.e.*, mainly by the weights. These two properties are practically independent of each other. It is on account of this essential difference that I consider a short time run as a test in principle unsuited for intermittently running machines.

Connection between the Temperature Rise under Working Conditions and that after a Short Full-load Run.—This contention will be objected to with the argument that a definite connection between the test result and the behaviour under working conditions is easily established, so that the former can be converted into the latter. I shall try to prove that this argument must be dismissed on theoretical and practical grounds.

We found the temperature rise under working conditions—

$$R_i = Rf,$$

and the rise after a full-load run of duration t—

$$r = R\left(1 - e^{-\frac{t}{T}}\right):$$

hence—

$$\frac{R_i}{r} = \frac{f}{1 - e^{-\frac{t}{T}}} = C \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

This ratio $\frac{f}{1 - e^{-\frac{t}{T}}} = C$ may be termed the conversion factor. If t is sufficiently short to justify the adoption of the straight line

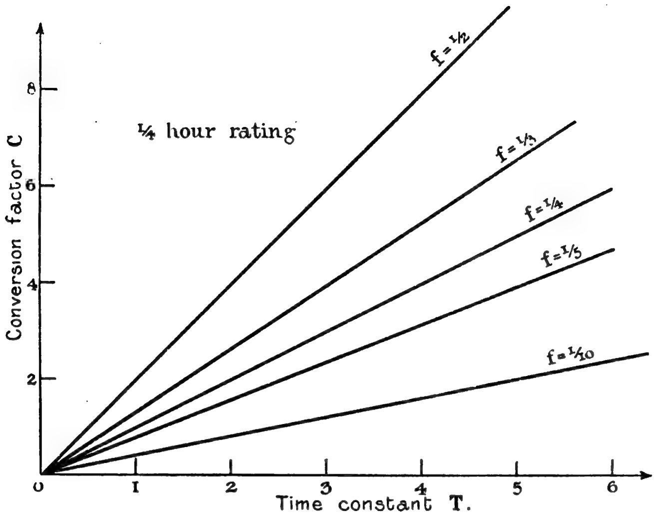
¼ hour rating
f = 1/2
f = 1/3
f = 1/4
f = 1/5
f = 1/10
Conversion factor C
Time constant T.
0
1
2
3
4
5
6
2
4
6
8

FIG. 3.

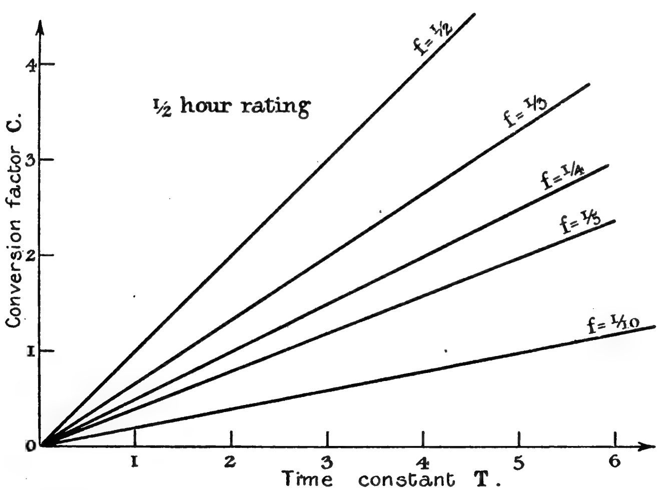
½ hour rating
f = 1/2
f = 1/3
f = 1/4
f = 1/5
f = 1/10
Conversion factor C.
Time constant T.
0
1
2
3
4
5
6
1
2
3
4

FIG. 4

$r_t = \frac{W\,t}{a}$ in place of the exponential curve the conversion factor assumes a much simpler form.

We have—

$$R_i = \frac{W}{b} \times f,\ r_t = \frac{W\,t}{a};$$

hence—

$$C = \frac{R_i}{r_t} = \frac{a}{b} \times \frac{f}{t} = \frac{T \times}{t} \quad . \quad . \quad . \quad . \quad . \quad (17)$$

The conversion factor for half-hour and quarter-hour rated motors is therefore 2 Tf and 4 Tf respectively, and this discloses the true significance of the time constant T. As soon as T is known, the conversion factor may be calculated or taken from curves such as given in Figs. 3 and 4, but without its knowledge no such conversion can be effected.

Everything depends, therefore, on the knowledge and the character of T.

The Time Constant T.—Unfortunately, however, the so-called time constant is of a rather complex nature. From (7), (12), and (15) we find—

$$T = \frac{a}{b} = \frac{\text{weight}}{\text{effective cooling surface}}$$

$$\times \frac{\text{heat distribution factor} \times \text{temperature rise of hottest accessible part}}{\text{temperature rise of surface}}$$

$$\times \frac{\text{specific heat}}{\text{specific dissipation}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (18)$$

The most important factor influencing T is the ratio—

$$\frac{\text{weight}}{\text{effective cooling surface}},$$

and for a series of machines developed on systematic lines the other factors of equation (18) may be considered as constant and T plotted as a function of this ratio. Fig. 5 shows this curve for a series of four polar totally enclosed motors of the Phœnix Dynamo Manufacturing Company. All these machines have cast-steel yokes, and it appears that T is $0{\cdot}65 \frac{\text{kilogrammes}}{\text{square decimetre}}$ or $4{\cdot}6 \frac{\text{lbs.}}{\text{square inch}}$. The smallest motor of the series which is of 10 H.P. at 900 revolutions and ¼ load factor has a time constant $T = 1{\cdot}35$, whilst for the largest of 100 H.P. at 400 revolutions we have $T = 3$.

Even larger variations of T for the same range of output are found in practice, and one may say that for motors from 5 to 100 H.P., T varies between limits as wide apart as 1 and 4. This variability would be less serious if T had at least a practically constant value known beforehand for all motors of a definite output, though of different make. But this is by no means the case; T depends largely on the design, as will be realised from a consideration of equation (18) only. Indeed, to be correct, it must be pointed out that T is not even constant for a given machine, because some of the factors forming it, chiefly the specific dissipation, depend on the speed. This applies to all machines, but particularly to motors of the ventilated type, and it results in the time constant of series-wound motors being dependent on the load.

The variability of T necessitates its experimental determination from heating and cooling curves, if any reliable information about the

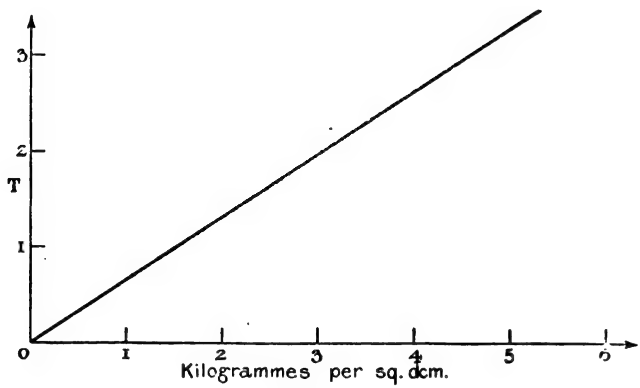

FIG. 5.

temperature under working conditions is to be obtained from the results of a short time run. Without experimental determination of T the results of a short time run are of little value.

The average purchaser of a crane-rated motor, however, cannot be expected to be conversant with these facts. Indeed, I cannot recollect a single specification relating to intermittently working motors which contained any reference whatever to the constant T, and I am convinced that not many engineers (excepting designers) have a clear conception of its significance.

There are rare instances in which the experienced crane-maker specifies 1-hour tests for the larger, and half-hour tests for smaller size motors, and occasionally special requirements are indicated. But the general practice is to specify half-hour tests indiscriminately and without any reference to the time constant or the load factor. To judge from the care with which the temperature at the end of the test is

measured, not many people seem to realise that a motor for, say, $\frac{1}{4}$ load factor may reach a temperature under working conditions anywhere between half and twice that found after a full-load run extending over half an hour. Chiefly from this knowledge I have come to the conclusion not only that short time tests are misleading, but that the conversion of their results by means of the time constant as repeatedly suggested is not a practical proposition, and cannot be accepted as a final solution of the problem.

Rating.—But let us look at the subject from the designer's point of view. The customary testing practice places the problem before him of producing a motor with a minimum cost of material which must be capable of giving a specified output for, say, half an hour without its temperature rise exceeding a certain limit. The loss in watts for a given output cannot very well be reduced below a known minimum, and the temperature after a run of half an hour $= \frac{W}{2a}$, depends otherwise only on the heat-storing qualities. There will thus be a natural tendency to adopting the latter as the basis of rating, and an endeavour to increase the heat capacity, so far as is reasonably possible, in order to enable a larger output to be obtained from an armature of given dimensions. With this end in view, a heavy cast-iron carcase may be used in place of a light steel frame, and the weight of the other inactive portions of the machine, such as bearing end plates, covers, armature bush, etc., may be increased, keeping at the same time the heat distribution factor as high as possible. On the other hand, there is little inducement to pay much regard to the cooling properties which do not directly enter the problem. By such means it is easily possible with hardly any increase in the cost of the motor to raise its heat capacity, and increase the rating by some 25 per cent. or more. But if we ask ourselves if these alterations of the design represent a real improvement, the answer will be decidedly in the negative. We know that the final temperature rise under working conditions does not depend at all on the weight but on the cooling properties, and as these are not appreciably improved, the alterations merely result in a larger time constant, but not in a genuine increase in the capacity of the machine under working conditions. Such methods of producing cheap crane motors can only be considered as illegitimate. They are made possible by the unfortunate practice of short time tests, which result in the temperature rise under the test conditions being dependent on factors entirely different from those which determine the temperature rise under working conditions.

The influence of the testing practice on the rating is also evident from the lists of quite a number of manufacturers showing the same output of crane motors whether they be totally enclosed or of the ventilated type. This again is due to the temperature rise after half an hour depending almost entirely on the weight and not on the cooling properties. In actual work the ventilated motor is, of course, capable of giving a larger output than the totally enclosed one, and it

could be rated higher than the latter, unless the limits of mechanical strength or of sparkless commutation are approached. This would be manifested if the heat dissipating qualities formed, as they should do, the basis of rating.

So we see the practice of short time tests, in addition to being deceptive, is leading the progress of design into wrong channels by establishing a false basis of rating. Indirectly, it retards healthy developments; such, for instance, as improvements in the dissipation from the surface of totally enclosed machines. A proposal to abandon the practice of short time tests altogether is therefore likely to find general support provided that another method of testing can be suggested which is free from the indicated defects.

The Requirements of a Suitable Test.—The test adopted should give direct and reliable information on the temperature rise of the machine under working conditions. It must take the load factor duly into account which in every instance is to be specified. The factors which determine the temperature rise during the test should be identical with those on which it depends under working conditions, *i.e.*, the heat dissipating qualities, and the method adopted must thus indirectly lead to the cooling surface, and not the weight being considered the basis of rating.

Finally, the test conditions imposed should be capable of being easily complied with by the ordinary testing plant and arrangements of the manufacturer.

Suggested Methods of Testing Crane Motors.—An ideal test would, of course, be one corresponding in every respect to the working conditions. For two reasons this ideal is incapable of attainment. The first is the practical impossibility of reproducing the exact starting conditions, and secondly, the duration of the working period is mostly so short as so make its reproduction a matter of very great difficulty. A compromise must be made with regard to both these points.

The real load curve must inevitably be replaced by a curve of more simple form, yet equal load factor and the duration of the working period will have to be extended. Thus we arrive at the *crane test with extended periods,* as suggested by Goldschmidt,* and by Broughton.† The latter employs a period of 12 minutes for any size of motor and any load factor. This means, for instance, 6 minutes running and 6 minutes rest for one half-load factor; 2 minutes run and 10 minutes rest for $\frac{1}{6}$ load factor. This test is to be carried on for a length of time sufficient to obtain a practically steady value of the mean temperature.

Such a test, however, especially for small load factors, requires almost continual and very careful attention, and an element of doubt is introduced due to the time required for bringing a motor from standstill to full speed, bearing a comparatively large proportion to the running time of each period. On this ground the suggested method is

* *Journal of the Institution of Electrical Engineers,* vol. 34, p. 690, 1905.
† *Electrician,* vol. 60, p. 120, 1907.

not free from objections, which is perhaps the reason for its failure to find much favour in practice.

Goldschmidt went a step further, and suggested a very much greater extension of the working period; for instance, to 30 minutes, consisting of 9 minutes running and 21 minutes standing in the case of 0·3 load factor. It is obvious, however, that the temperature found immediately after the 9 minutes' run will be appreciably above the mean temperature, and the difference will be the greater the smaller the machine.

Probably on this account he recommended to shorten the period for small machines and to extend it still further for large ones.

It is hardly desirable, however, to have different tests for different sizes of machines, and any method adopted as standard should, if possible, be uniformly applicable.

This difficulty may, however, be easily overcome. We need only

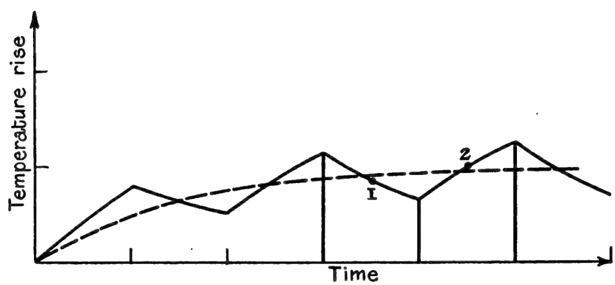

FIG. 6.

take the temperature not immediately after the last run, but after one-half of the standing time has elapsed, or, alternatively, we may limit the last run to one-half of the ordinary running time, and then take the temperature immediately the motor stops. Due to the curvature of the heating and the cooling curves (see Fig. 6), the temperature with the first method (point 1) will be somewhat below, with the second (point 2) somewhat above the mean temperature.

If this is being done, there is no objection to a very great extension of the working period. It would be advisable, however, not to specify the length of the whole period, but the duration of the running time, which for all load factors might be taken as 10 minutes. This would bring us to the following specification:—

The temperature rise of machines for intermittent working shall be found by subjecting them to a prolonged test consisting of successive periods of running and of rest. The running time to be 10 minutes, the standing time adjusted in accordance with the specified load factor; the duration of the test to be sufficient for the mean tempera-

ture to attain a practically constant value. The last run to be of 5 minutes duration, immediately after which the temperature is to be measured.

A crane test with extended periods as here suggested can be carried out without great difficulty, and it meets all the requirements which have been enumerated. I am aware, however, that there is some disinclination on the part of the manufacturers to adopt as a standard test one requiring frequent starting and stopping, and on this account I wish to make an alternative suggestion.

A Crane Test with Continuous Load.—As pointed out before, to arrive at a practicable test a departure from the actual load curve is unavoidable. There is no serious objection to this so long as we make sure that the change introduced does not materially affect the temperature rise. This being the case, we may take the bold step of replacing the curve of irregular and intermittent load by one of constant and continuous load, adjusted in such a manner that the loss becomes practically equal to the mean loss W_m under working conditions. This condition, however, must apply not only to the motor as a whole, but also to its individual parts, so that the distribution of the losses remains practically unaffected.

Now, according to the definitions adopted, W_m is with close approximation equal to $W \times f$, and our object will be obtained, though not accurately, yet nearly enough for practical purposes, if we run the motor continuously with its pressure and current reduced in proportion to the square root of the load factor, *i.e.*—

$$\text{Test voltage} \ldots = \sqrt{f} \times \text{normal voltage.}$$
$$\text{Test amperage} = \sqrt{f} \times \text{normal amperage.}$$

For the load factors $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$, and $\frac{1}{5}$ the continuous test is to be carried out with 0·71, 0·57, 0·50, and 0·45 respectively of the normal current and pressure. It is obvious that first of all the copper losses throughout the motor will be exactly f times the copper losses at full load, as desired, and this applies both to the armature and field, whether the motor be shunt or series wound.

The iron losses in the armature are also reduced approximately in the desired proportion on account of both the flux and the speed being smaller than the normal. The friction losses are the only ones which are reduced appreciably less than in the desired ratio.

Taking the sum of all the losses, we find they are very little higher than $W \times f$. I have worked out the losses in the case of 3-crane motors at full load and also for a test according to the square root of f rule for $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$, and $\frac{1}{5}$ load factor, and the result shows that the average excess of the total losses during the test over $W \times f$ is only $4\frac{1}{2}$, 8, $11\frac{1}{2}$, and $13\frac{1}{2}$ per cent. for $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$, and $\frac{1}{5}$ load factor respectively.

As will be seen, it is chiefly the excess of the friction loss which causes the total loss during the continuous test to be larger than $W f$.

But this is not a serious objection. In fact, it is desirable that it should be so for the following reasons :—

We defined at the outset the load factor f as the ratio (virtual load)^2 to (full load)^2 and as distinct from the older definition $\frac{t'}{t' + t''}$. In doing so, we intended maintaining, as nearly as possible, the connection $W_m = W \times f$. This object is obtained with regard to the copper losses and approximately so with regard to the iron losses, but the mean friction losses are dependent on the time of running. Now $\frac{t'}{t' + t''}$ is invariably greater than f, and in the case of series motors the friction loss is even increased during the periods of reduced load on account of the rise in speed (see Fig. 8). The same remarks apply to a lesser extent to the iron losses. In consequence W_m is actually somewhat greater than $W \times f$, and we may say that the continuous test as above suggested corresponds with great accuracy to average working conditions so far as the losses in all parts of the motor are concerned.

This being the case, it will be applicable to all stationary machines, such as transformers, and also sufficiently accurate for totally enclosed motors for intermittent working. The curves (Fig. 7) representing the test results of a 40-H.P. motor will further prove this contention.

Application of the Continuous Test to Ventilated Machines.—A serious objection, however, seems to stand in the way of the employment of a continuous test for all ventilated motors. The temperature of these machines being dependent not only on their losses, but to a large extent on the effectiveness of their ventilation, it will be argued that in spite of the equality in losses, the temperature rise after a continuous test must be lower than it will be under working conditions, when the motor is standing for a considerable portion of its working period. To what extent this argument is correct depends firstly on the importance of the ventilation on the temperature rise generally. In this connection it must be remembered that nearly all crane motors are slow-speed machines.

It will also be observed that the ventilation during the continuous test, according to the above suggestion, is reduced on account of the reduction in speed. For instance, the motors of Table I. during the continuous test, corresponding to $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$, and $\frac{1}{5}$ load factor, would run with an average of 74, 64, 59, and 56 per cent. respectively of their full-load speed. Finally, it must again be pointed out that an intermittently working motor revolves in practice for a much greater portion of the total period than its load factor f indicates (see curve B, Fig. 1). In the case of series motors the ventilating effect is still further increased during the periods of reduced load on account of the rise in speed. The temperature rise of an intermittently working motor of the ventilated type depends therefore not only on the load factor but on the whole shape of the load curve. This will be clearly realised from

a consideration of the speed curves (Fig. 8), and a comparison of curves B and C demonstrates that the ventilation during the continuous test is not necessarily better than it is under working conditions. Considering the uncertainty as to the temperature rise of ventilated motors due to

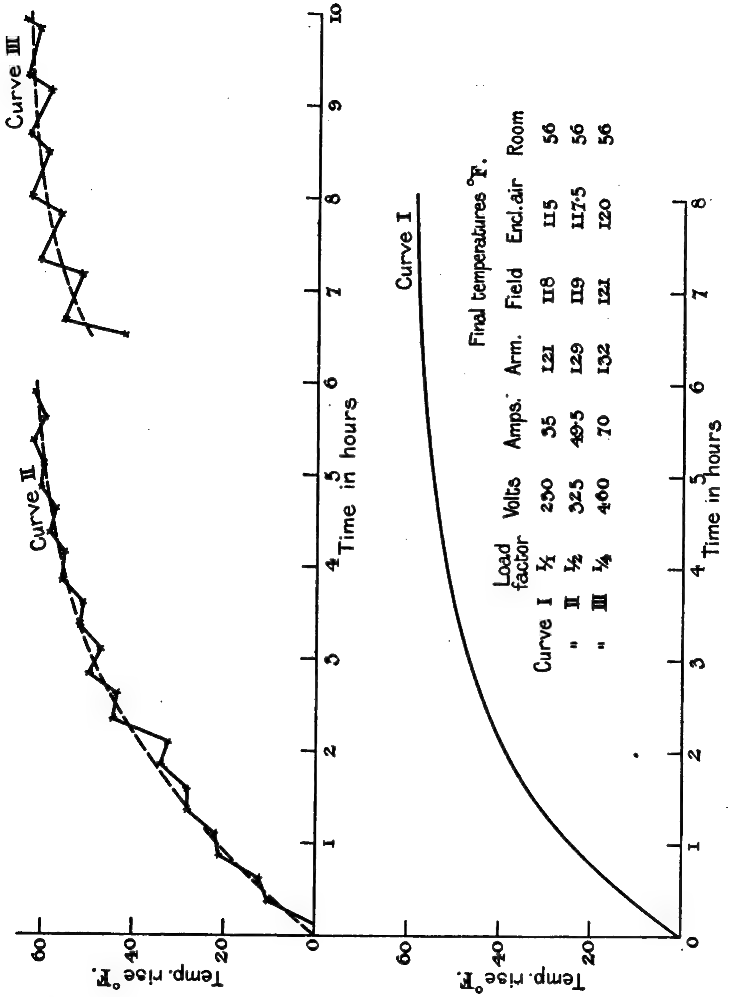

FIG. 7.

the large variety of load curves corresponding to the same load factor which are found in practice, I come to the conclusion that the continuous test is applicable to ventilated machines as well as to totally enclosed ones.

TABLE I.

Load Factor f.	$\frac{1}{1}$.	$\frac{1}{2}$.	$\frac{1}{3}$.	$\frac{1}{4}$.	$\frac{1}{5}$.
$\sqrt{f}$.	1.	0·707.	0·577.	0·5.	0·447.
11¾ H.P., 220 VOLTS, 49 AMPERES, 630 REVS.					
Volts	220	156·0	127·0	110·0	98·5
Amperes	49	34·6	28·3	24·5	22·0
Revolutions	630	460·0	395·0	363·0	340·0
Per cent. of full-load speed	100	73·0	62·8	57·5	54·0
Iron losses	156	90	66	52	43
Copper losses	1,715	857	572	428	343
Bearing and brush friction	105	77	66	60	56
Contact losses	98	58	43	35	29
Total losses	2,074	1,082	747	575	471
Excess of losses over W × f	0	4%	8%	11%	13%
26½ H.P., 220 VOLTS, 109 AMPERES, 500 REVS.					
Volts	220	156·0	127	110·0	98·5
Amperes	109	77·0	63	54·5	49·0
Revolutions	500	367·0	315	292·0	272·0
Per cent. of full-load speed	100	73·5	63	58·2	54·2
Iron losses	254	153	107	87	70
Copper losses	3,380	1,690	1,130	845	675
Bearing and brush friction	191	140	119	111	104
Contact losses	218	129	96	77	65
Total losses	4,043	2,112	1,452	1,120	914
Excess of losses over W × f	0	4·5%	7·5%	11%	13%
118 H.P., 440 VOLTS, 222 AMPERES, 400 REVS.					
Volts	440	312·0	254·0	220·0	197·0
Amperes	222	157·0	128·0	111·0	69·0
Revolutions	400	302·0	265·0	246·0	234·0
Per cent. of full-load speed	100	75·2	66·2	61·3	58·5
Iron losses	630	372	267	210	177
Copper losses	8,080	4,040	2,700	2,020	1,615
Bearing and brush friction	465	351	308	287	272
Contact losses	444	264	195	157	133
Total losses	9,619	5,027	3,470	2,674	2,197
Excess of losses over W × f	0	4·5%	8·5%	12%	14·5%

I do not contend that it gives exact information on the temperature rise under working conditions in every instance, but suggest that it meets the fundamental principles and all reasonable requirements to which a method of testing the large class of intermittently working machines should comply.

Modifications of the Continuous Test for Shunt Motors, etc.—As pointed out before, in the case of shunt-wound crane motors, we have to distinguish between the load factor of the armature $f_{\text{arm.}}$ and that of the field $f_{\text{field.}}$ It will be found in most cases that they do not differ much

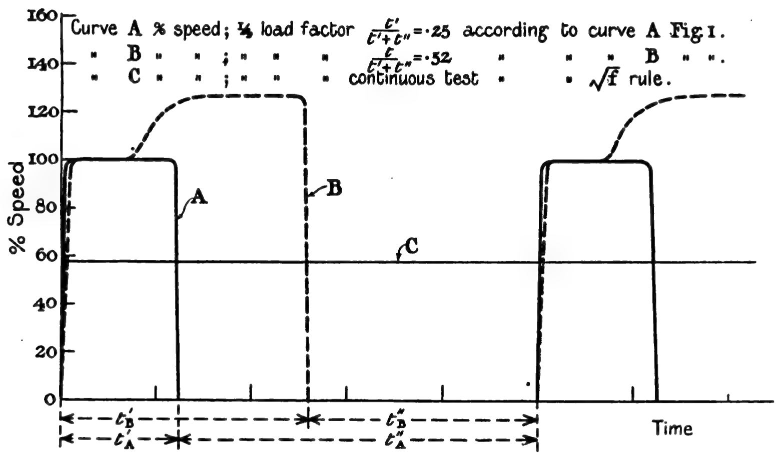

Fig. 8.

from each other, and that the test as above described is directly applicable. Otherwise the following modification of the continuous test might be specified :—

$$\text{Test voltage} \ldots = \sqrt{f_{\text{field}}} \times \text{normal voltage.}$$
$$\text{Test amperage} = \sqrt{f_{\text{arm.}}} \times \text{normal amperage.}$$

The continuous test is also applicable to all alternating-current machines, where necessary, with slight modifications.

Conclusion.—Whatever substitute for short time tests may in future be adopted, the present practice can no longer be considered as being in accordance with scientific principles. No doubt this subject will be carefully investigated in connection with the framing by this Institution of definite rules on the rating and testing of all electrical machines, and I hope this will not be much longer deferred.

Discussion.

Mr. Hartnell.

Mr. Wilson Hartnell: The ordinary testing of enclosed motors is most unsatisfactory and the statements regarding them made by various makers are misleading. Dr. Pohl has put the matter before us in almost abstract form, but it seems to be one of those subjects which does not lend itself to an abstract discussion. In abstract reasoning on a complicated subject one should be able to ignore many facts, as being of minor importance, and to deal clearly with the main matters. Here the difficulties of obtaining a formula or mode of testing that will enable the final temperature of an enclosed motor to be predicted from a brief test seem almost insuperable on account of the many unknown variables of almost equal importance. I investigated this subject from an experimental point of view, and published the results two years ago.* I thoroughly agree with Dr. Pohl wherever he has touched on practical points, especially on page 219 regarding the heating and cooling curves, but he does not say very much about the cooling curve. The tangents to the beginning of the heating curves of the first nine motors on Table I., page 491 of my paper, may be drawn by dividing 72 on a vertical scale of degrees by the figures in the last column of Table I. measured from a horizontal scale of minutes. I found that although the heating and cooling curves of different sizes of motors have a general resemblance, they are far from identical. The larger the enclosed motor the higher the final temperature. Thus I was forced to the conclusion that no large totally enclosed unventilated direct-current motor could be run at full load continuously. Dr. Pohl states that the heating and cooling curves approximately represent the logarithms of the ratio of two factors. This may be so, but the factors themselves are involved quantities, only discoverable by experiment. It would be interesting to have the complete heating and cooling curves of two enclosed motors. I entirely agree with him that from such curves the final temperature of the motor under intermittent loads could be found by means of a zigzag line such as he has shown and described on his diagram on page 219, Fig. 2. Practical engineering obliges us to search for truth by statistical methods where the result depends on many indeterminate variables. Having experimentally obtained a complete standard curve for a given motor, the test of a similar (or nearly similar) motor need only be carried far enough to obtain the tangent, and say, three points in the heating curve. The complete curves can then be surmised and drawn from the standard curve (see Fig. 4, page 223). By this means the behaviour of an enclosed motor under all ordinary circumstances can be demonstrated from a short test in a convincing manner, and with sufficient accuracy for all practical purposes.

Mr. Cridge.

Mr. A. J. Cridge: It is not immediately obvious why the ratio mentioned should be the load factor. It seems to me that if the area

* *Journal of the Institution of Electrical Engineers*, vol. 41, p. 490, 1908.

Mr. Cridge.

of the current curve as taken on a recording ammeter were divided by the area of the rectangle representing the product of the maximum current and the total time, the ratio would correspond more nearly to what is generally called load factor. If Dr. Pohl has come to the conclusion that the two ratios are usually identical, I would ask him to tell us something of the way in which he has done so. The curves and data asked for by Mr. Hartnell would, no doubt, be very interesting, but I rather approve of the way in which the author has reduced them to general equations, and with a little expansion I think they would be sufficiently practical for manufacturing purposes. I am prepared to agree with Dr. Pohl that the present practice in regard to the testing of motors for intermittent use is not satisfactory, and I think that the Institution ought to lay down some rules not only for this but for other testing work. This has been done in America with very great advantage to electrical engineers there. I was rather surprised to see what an extremely variable quantity the time constant of a motor is; it seems to vary with almost every conceivable condition; it alters with the heating curve, with the cooling curve, with conditions of running, and in a different way with different motors. It would seem open to question whether it should be regarded as a constant at all.

Mr. Yerbury.

Mr. H. E. YERBURY: In my opinion it would be advisable to dissociate traction motors for tramways from such admittedly intermittent work as cranes, hoists, and lift motors. Now that electric braking is being used to such a large extent in tramway work, one cannot look upon motors for traction work as machines for short period working. The guiding principle enunciated by Dr. Pohl that the testing of any finished machine should accurately represent its future working conditions may be satisfactory from a designer's or manufacturer's standpoint; but I would go further, and from a user's standpoint suggest that a machine should be subjected to continuous load above that for which it would be normally run. In the case of traction motors the usual period of test is four hours full load, but I should say for crane and lift work a shorter test would be satisfactory, especially if it be a full-load continuous one. Undoubtedly the heat generating ability and heat dissipating quality of a motor are most important matters, and in my experience trouble with motors of all classes has been invariably traced to overheating and consequent failure of insulation. I am pleased to hear that the author considers a very short time run unsuited even for intermittent running machines, and also that he favours cast-steel yokes for motors. I find some contractors prefer to use cast-iron yokes, and do not like cast-steel yokes to be specified, presumably because they are not in a position to cast them in their own shops. I agree with the author that there should be an established basis of rating and testing for all machines, but manufacturers should always be in a position to quote to an engineer's specification, for instance, respecting temperature rise for a machine working under exceptional conditions. Standardisation is

Mr. Yerbury. good, but the conditions of working often require specially designed machines.

Mr. Ingleby. Mr. J. C. B. INGLEBY: There are several factors mentioned in the paper which, to the best of my knowledge, are still found experimentally and dealt with by rule-of-thumb methods or by interpolation of the results. It is not easy to predetermine the ratings of a totally enclosed motor, but it appears to me that the method of circulating the air inside the motor has a great deal to do with the temperature rise in such machines. For instance, taking a 20-H.P. motor with a one-hour rating, and a speed of 775 revs. per minute, if this motor were rated for half an hour, the speed could drop to about 510 revs. per minute, or for a quarter-hour rating to about 350 revs. per minute. The temperature coefficients mentioned by the author would take a long time to find, and no doubt would soon have to be found again owing to some drop in motor prices necessitating slight changes in the general design.

Mr. Wardale. Mr. W. T. WARDALE: I would like to call attention to one point that appeals to me as worthy of consideration when dealing with the subject of intermittently working motors. I believe the auxiliary motors on the battleships of our Navy are tested as intermittently working motors, and the author has mentioned the first half-hour of the test is misleading, because if the motors are working in connection with ammunition hoists on these ships, in the event of a long fought action the temperature of the whole ship would go up tremendously, and further, every shot which the ship received would, of course, strain to some extent the whole ship's framework, and it is quite possible the guides on which the hoists run may be jammed. If these motors gave out at a critical time, it would be a serious matter. With regard to designers taking the risk of using cast-iron yokes, I think in the long run they will reap what they deserve, because such motors will get classed as those that may stand the test on the test-plate, but will not do the work outside. I would like to suggest that the author should test in the ordinary way on the test-plate with a set of motors for a crane and afterwards equip a crane with these motors. If this were done over a full working day some valuable relation might be established between the practical working conditions and the test-plate conditions. We might then find an approximate ratio between test-plate conditions and working conditions, which would be a useful guide when designing such motors.

Dr. Pohl. Dr. POHL (*in reply*): Mr. Hartnell pointed out that the cooling is very much more intense when the motor is hot than when it is cool. The heating and cooling portions of the main curve on page 219 exactly conform to the heating and cooling curves shown in the same diagram and clearly illustrate this point. Mr. Hartnell further suggested that a series of tests should be carried out to ascertain exactly the heating and cooling curves of a number of motors, and that from such curves it would be possible to find out beforehand what the running conditions would reveal. I have taken a number of such

curves for direct-current and alternating-current machines, both of the totally enclosed and open type, but did not think it worth while to include them in the paper because the results of such tests have already been published. Curves of that kind are given in Goldschmidt's paper.* The investigation of the working results by means of heating and cooling curves has been suggested by various authors I have referred to, and no doubt reliable results can be obtained in this manner. Having found the time constant for running at a certain speed, one can draw the whole of the heating curve, and from the time constant for cooling the cooling curve may be drawn. Under an intermittent load with any given load factor it will then be possible to draw a curve such as shown in Fig. 2, and it will almost exactly represent what is obtained in practice. But the time constants must be actually found by experiment, because a guess might easily be wide of the mark. It is on this account that I think such procedure is far too complicated as a standard test for intermittently working motors. What is wanted is one simple test which gives the required information directly, and that is the essence of my paper. Dr. Pohl.

The time constant is a most complicated figure, and as Mr. Hartnell pointed out, there are a large number of constants which affect the heating and cooling, yet the interesting fact remains that in investigating any practical curves, one finds they can be expressed with sufficient accuracy by the exponential equations given. My experience agrees with that of Mr. Hartnell, that 3-phase motors when totally enclosed show more satisfactory results than direct-current machines. I believe this to be due to the cast-iron casing being in close touch with the stampings which are the seat of a great part of the losses, and also to the very small gap between stator and rotor, which facilitate the rapid transfer of the heat from the interior to the surface.

Mr. Cridge expressed some doubt as to whether my definition of the load factor—equation (3)—is correct. I put it forward as a suggestion and am inclined to think that it is largely a matter of choice what definition one adopts, so long as it is clearly stated. The reason why I put it in the form $f = \frac{(\text{virtual current})^2}{(\text{full-load current})^2}$ is, first, that by so doing the connection $f = \frac{\text{mean loss under working condition}}{\text{loss at full load}}$ is maintained, and secondly, that it comprises as a special case the older definition $f = \frac{t'}{t' + t''}$. One may test this latter point by a concrete example.

Mr. Cridge further objected to the "time constant" being called a constant seeing that it is such a variable quantity. I am in the fullest agreement with him. It has, however, always been termed "time constant" in technical literature, and this may be an excuse for my use of the term. Mr. Hartnell pointed out that it was not of much use to put a fan into a totally enclosed motor. This agrees entirely with my own experience. Mr. Yerbury wished to

* *Journal of the Institution of Electrical Engineers*, vol. 34, p. 660, 1905.

Dr. Pohl. dissociate traction motors from crane motors. I do not, however, see that this is necessary, because in principle they can be treated in the same manner, although their duty is in most cases very much heavier. Heavier duty simply means that the specified load factor for which they must be tested is correspondingly higher. I might mention, as a concrete example, that some large railway motors recently supplied for most onerous duty on express-passenger trains were, in accordance with the specification, designed and tested for load factor unity, *i.e.*, for continuous running on full load. I would suggest that if a diagram of operations be drawn for a traction motor, corresponding to the heaviest loads the motor may be called upon to deal with under the most unfavourable conditions, and that duty be specified in terms of the load factor, then a motor complying on the test-bed with that specification will certainly prove satisfactory in practice. This will meet Mr. Yerbury's point, that a motor should be tested above what it has to do. It is the purchaser who should make sure of this, by specifying a load factor which corresponds not to the normal but the heaviest possible duty. Manufacturers cannot be expected to test motors above what is specified. Motors are ordered to requirements, and the manufacturer's duty is to prove on the test-bed that the motor is in every respect in conformity with the specified conditions.

I can confirm what Mr. Wardale pointed out, that motors for ammunition hoists for the Navy are specified to be tested intermittently for a great length of time. I believe this is a case which meets Mr. Yerbury's view. The heaviest possible duty which the motor may be called upon to perform is specified as the normal duty of the motor. Mr. Yerbury's experience as to the use of cast-iron yokes by some contractors confirms my remarks on that point. I also agree with him that manufacturers should be capable of dealing with the requirements of buyers when specially designed machines are needed. At the same time, I maintain that at present a large number of machines are special ones and in consequence more expensive, which need not be special at all. This is due to the absence of rules on the rating and testing of machines, backed up by a competent authority. Purchasers would refer to such rules instead of putting their own divergent and sometimes crude notions on paper and insisting on a strict adherence to the same.

ORIGINAL COMMUNICATION.

GRAPHICAL TREATMENT OF THE ZIGZAG AND SLOT LEAKAGE IN INDUCTION MOTORS.

By R. E. HELLMUND.

(*Received June* 1, 1909. *Revised May*, 1910.)

In a paper read before the National Convention of the American Institute of Electrical Engineers at Atlantic City the author gave certain graphical methods for the study of the main field in induction motors.* It is the purpose of the present paper to employ similar methods for the investigation of the zigzag and slot leakage fluxes and their effects. Incidentally a number of factors which are required for the practical design of induction motors will be derived. The results obtained in the paper are given in a condensed form in the Appendix, where they are also transformed into simple expressions, which I believe are exact enough for all practical purposes.

DEFINITIONS.

1. *Leakage Coefficient.*—The leakage coefficient is one of the chief factors upon which a number of customary methods of designing induction motors as well as methods for the experimental investigation of induction motors are based, and it is partly for this reason that this factor is dealt with at some length. The chief reason for determining this value is, however, the fact that it fixes directly the excellence of a motor in almost every respect, and therefore the values obtained for this factor form a direct means for determining the relative merits of various designs. If properly designed, a motor will always be better the smaller the leakage coefficient. This fact alone seems to the author sufficient to make methods of designing based on the leakage coefficient more desirable than others. Another reason why the author prefers to work with this coefficient is that the expressions for calculating it are simpler than those which take the leakage phenomena into account in some other way, assuming, of course, that they are equally exact. This is to be expected, because the leakage coefficient, no matter how it is defined, is always a ratio between the effects of the leakage field and the main field. These contain a number

* *Transactions of the American Institute of Electrical Engineers*, vol. 27, p. 1373, 1908.

of common factors which influence both fields, eliminating each other in the formula for the leakage coefficient. As pointed out in one of the author's papers on "Zigzag Leakage,"* the definition for the leakage coefficient varies greatly with different writers. This is probably due to the complexity of the induction motor phenomena, which make it difficult to give a definition equally well suited for all purposes. There is one value for the leakage coefficient, however, which is most frequently used in practice, and I shall proceed to determine this value in the present investigation, without going further into a discussion concerning the relative merits of the various definitions. This definition is given by the following equation—

$$\sigma = \frac{i_m}{i_b}, \quad \ldots \ldots \ldots \quad (1)$$

where i_m is the magnetising current of the light-running motor and i_b the stator current, while the rotor is locked and short-circuited; both values under the assumption that the losses in the motor are zero—*i.e.*, that the circuits are purely reactive circuits. Both values apply, of course, to the same impressed potential.

The above formula for σ may be changed into a form which is more convenient for the succeeding operations. Let the potential, which calls for a no-load magnetising current i_m, be e_m. In order to obtain the same current value i_m for the locked rotor condition the potential must be reduced to a value—

$$e_b = e_m \frac{i_m}{i_b},$$

under the assumption that the magnetic reluctance of the iron is independent of the density. It follows, therefore—

$$\frac{e_b}{e_m} = \frac{i_m}{i_b},$$

and—

$$\sigma = \frac{e_b}{e_m} \quad \ldots \ldots \ldots \quad (2)$$

Since the potentials induced in the motor must be equal and opposite to the impressed potentials, we may consider e_b in formula (2) as the potential induced per phase in the locked rotor condition, and e_m the potential induced while the rotor is running with synchronous speed, the same stator current being assumed in both cases. With this modified definition the leakage coefficient may be easily determined, since the potentials induced under the assumption of a certain current are given for the no-load condition by the diagrams of my previous paper,† and for the locked condition by the diagrams in the following investigation.

* *Transactions of the American Institute of Electrical Engineers*, vol. 26, p. 1505, 1907.

† Ibid., vol. 27, p. 1373, 1908.

2. *Effective Tooth Width.*—As is well known, the magnetic flux between the tooth of one member and the pole-face of the other member spreads to a certain degree near the edge of the tooth. An exact analysis of this dispersion for all the practical forms of teeth is next to impossible. Carter has, however, given derivations for some of the simpler forms, and the results obtained by him will be utilised as far as possible, in other cases approximate methods will be introduced.

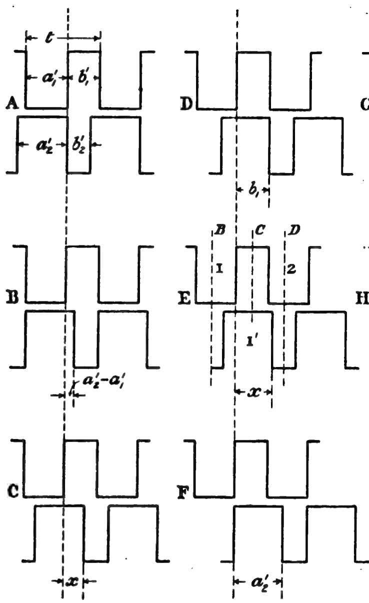

FIG. 1.

In considering the dispersion of the flux of one tooth distinction must be made between two possible cases.

1. When the adjacent tooth of the same member is of the same polarity as the tooth under consideration.
2. When the adjacent tooth of the same member has a polarity opposite to that of the tooth under consideration.

Carter has worked out for both of these cases coefficients, by the aid of which the effect of the dispersion may easily be taken into consideration. For the following studies his results may be best utilised by introducing an effective tooth width, whereby is meant the width of a tooth which would have the same total reluctance under the assumption of no dispersion.

This effective tooth width a' may be found from—

$$a' = A \times 2\,\xi' \times g \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where A is the actual tooth width, g is the length of the air-gap at one side of the rotor, ξ' is found from the upper curve of Fig. 15 for the first of the two possible cases and from the lower curve for the second one. In such cases of partially closed slots, where $d_1 < \frac{B_1}{2}$ (see Fig. 21), more exact results will probably be obtained if the value ξ', corresponding to the value $\frac{2}{g} r_4$, is taken from the curves (see Fig. 15). The effective width of the slot is found, of course, from—

$$b' = t - a' \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where t is the slot-pitch.

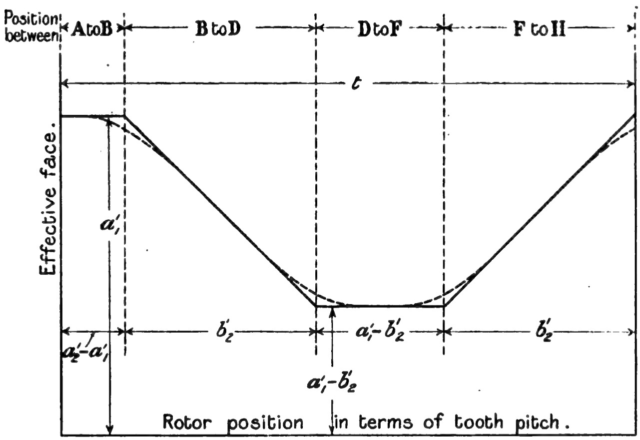

FIG. 2.

NO-LOAD CONDITION.

1. *Gap Factor.*—The total field induced by a certain number of ampere-turns depends, of course, largely upon the effective width of the teeth, which determine the effective size of the pole arc. The latter changes with the rotor position, and its average is best determined by assuming an equal number of teeth in both members.

The full line (Fig. 2) represents the active pole arc values as derived under the assumption previously made, and in accordance with the dimensions indicated in Fig. 1, A to H, while the actual values are probably close to those given by the dotted curve. Since the average values for the two curves are, however, very much alike, we may derive them from the full-line curve. We thus find the average from the two figures to be—

$$a_e = \frac{a'_1 \, a'_2}{t} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

If we make $a'_1 = c'_1\, t$ and $a'_2 = c'_2\, t$, we get—

$$a_e = c'_1\, c'_2\, t \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

as active pole arc per tooth. If we have N_1 teeth per pole, we obtain for the active pole arc—

$$\psi = a_e\, N_1 = c'_1\, c'_2\, t\, N_1 = c'_1\, c'_2\, \tau \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

where τ is the pole-pitch.

This value has been derived from an equal number of teeth in both members. A simple consideration shows, however, that it also applies to an unequal number of teeth after the tooth width is expressed in terms of the tooth-pitch, as is the case in formula (7).

The average gap factor is now—

$$G = \frac{\tau}{c'_1\, c'_2\, \tau} = \frac{1}{c'_1\, c'_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

2. *No-load Field and Potential for Full-pitch Windings.*—The detailed derivation of these values is given in the previous paper. It remains only to establish certain relations regarding the size of the vectors as influenced by the gap factor, number of slots per pole, etc.

(*a*) *Two-phase Motors.*—If the total magnetising effect per phase is proportional to C, one side of the square diagram which gives the magnetising effect exerted upon the individual teeth (Fig. 3, previous paper,* also Fig. 3(*b*) of this paper) is proportional to C also.

If we now assume the reluctance of one pole-face with entirely closed slot to be R, the reluctance of a pole-face with open slots will be R × G, and the reluctance per tooth will be—

$$R_t = R \times G \times N_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

The size of the one side of the square diagram representing the fluxes in the individual teeth should therefore be proportional to—

$$\frac{C}{R \times G \times N_1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

where N_1 = number of slots per pole in the primary.

If this be used as a base, we find by a very simple consideration, from the figures of the previous paper, that the potential e_m induced per phase at no load will be proportional to—

$$e_m \propto \frac{C \times k \times w}{2\, R G},$$

where w is the number of turns per phase and k a coefficient given in the previous paper.†

* *Transactions of the American Institute of Electrical Engineers*, vol. 27, p. 1376, 1908.

† Ibid., vol. 27, p, 1386, 1908.

(*b*) *Three-phase.*—The derivation for 3-phase motors is very similar to that outlined above. If we again assume the magnetising effect per phase to be proportional to C, we find the size of one side of the hexagon, which gives the magnetising effect exerted upon the individual teeth to be proportional to $\frac{C}{2}$, and obtain—

$$e_m \propto \frac{C \times k \times w}{3 \times R \times G} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

3. *No-load Field and Potential for Fractional Pitch Windings.*—(*a*) *Two-phase:* The diagram showing the effect of chording the primary winding upon the no-load field and the potential have also been shown in the previous paper.* The value of the coefficients to be introduced on account of the chording have been determined by the author from such diagrams.†

It follows from these figures that the potential induced at no load (e_m) for chorded windings is proportional to—

$$\frac{C \times k \times c \times w}{2 \times R \times G} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

where—

$$c = \sin^2 \frac{a}{2},$$

approximately a being the coil-pitch in electrical degrees.

(*b*) *Three-phase.*—In a like manner we find for 3-phase fractional pitch windings—

$$e_m \propto \frac{C \times k \times c \times w}{3 \times R \times G} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

Zigzag Leakage.

1. *Entirely Closed Slots and Full-pitch Winding—Number of Slots the Same in Both Members.*‡—(*a*) *Two-phase Motors*: In Fig. 3(*b*) the diagram for the tooth magnetomotive forces for the winding of Fig. 3(*a*) is reproduced from Fig. 3 of the previous paper.§

Under the assumption of a uniform air-gap reluctance the vectors of the diagram may also be considered to represent the fluxes in the primary teeth. According to our definition of the leakage coefficient the secondary must be considered to have a resistance equal to zero and be in stationary and short-circuited condition, while the leakage fluxes are investigated. Under these assumptions currents will be set up in the secondary squirrel-cage winding, which reduce all fields in

* *Transactions of the American Institute of Electrical Engineers*, vol. 27, p. 1373, 1908.
† *Electrical World*, vol. 52, p. 1342, 1908.
‡ The subject matter of this paragraph has been previously published in the *Elektrotechnische Zeitschrift*, vol. 30, p. 25, 1909. A repetition will, however, be advisable here for the sake of completeness.
§ *Transactions of the American Institute of Electrical Engineers*, vol. 27, p. 1376, 1908.

the secondary teeth to zero, if we neglect at the moment the effect of slot and end connection leakage. This must be the case because it is the only possible condition of equilibrium for squirrel-cage winding of zero resistance.

If we assume for a moment a flux passing through any of the rotor teeth we know that potentials will be at once induced in the secondary, and currents will be set up which counteract this flux and reduce

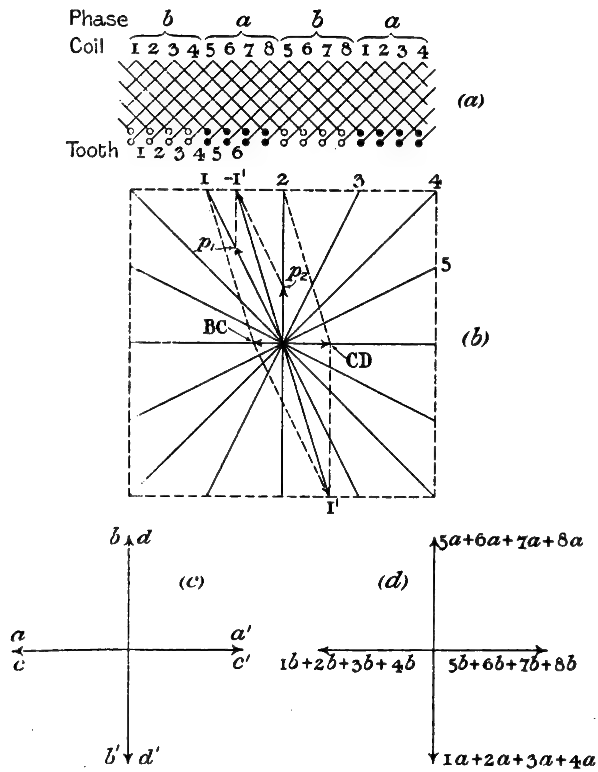

FIG. 3.

it to zero. It follows, therefore, that the magnetomotive forces impressed by the rotor currents upon the rotor teeth must be such that, assuming the stator to be without current, they will induce fluxes in the rotor teeth equal and opposite to the fluxes which the stator current sends through the rotor teeth, while the rotor is without current; or, in other words, the effect of the stator and rotor currents upon the rotor teeth must be equal and opposite to each other in order to reduce the flux to zero, while the currents in both members are

flowing. Fig. 4—corresponding to Fig. 3(*a*), a 2-pole winding—shows stator and rotor with eight slots per pole.

The rotor teeth are assumed to be shifted an angle x against the stator teeth. Let us now consider, for instance, the rotor tooth 1′. While there is no current in the rotor, this tooth receives from tooth 1 a part p_1 of flux 1 and from tooth 2 a part p_2 from flux 2—see Fig. 3(*b*).

We find from Fig. 4—

$$p_1 = \overline{1}\,\frac{t - x}{t}\ *$$

and—

$$p_2 = \overline{2}\,\frac{x}{t}.$$

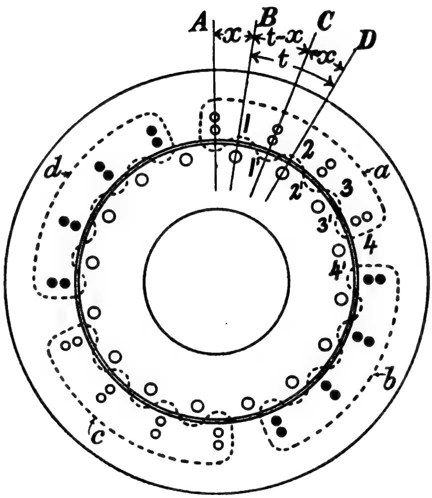

Fig. 4.

The resultant $\overline{-1'}$ of p_1 and p_2 represents, then, the flux of the rotor tooth 1′ under the assumption of no current in the secondary.

The vector $\overline{1'}$, being opposite and equal to $\overline{-1'}$, represents therefore, as outlined before, the flux which would be induced by the rotor currents under the assumption that no primary currents are flowing.

Introducing the corresponding change of scale, the vector $\overline{1'}$ may also be considered to represent the magnetomotive force impressed upon the rotor tooth 1′ by the secondary currents. It is now possible to determine the resultant magnetomotive forces acting upon the air-gap between B and C, and between C and D (Fig. 4).

We see from Fig. 3B that the magnetomotive force acting between B and C is the resultant $\overline{BC}$ of the vectors $\overline{1}$ and $\overline{1'}$.

* A line over any figure is intended to indicate that the figure represents the corresponding vector,

The magnetomotive force between C and D is the resultant $\overline{CD}$ of the vectors $\overline{2}$ and $\overline{1'}$.

The size of this resultant magnetomotive forces can be easily determined from the figure. We have found before that one side of the square diagram representing the magnetomotive forces is equal to C. One division of the square side is therefore proportional to $\frac{2C}{N_1}$, since each side is divided in $\frac{N_1}{2}$ divisions.

The size of the vector $\overline{BC}$ follows, therefore, from a simple geometrical derivation to be—

$$\frac{2C}{N_1} \times \frac{x}{t},$$

and similarly we find—

$$\overline{CD} = \frac{2C}{N_1} \times \frac{t-x}{t}.$$

The reluctance per tooth for entirely closed slots is—

$$R_t \propto R \times N_1.$$

The reluctance between B and C therefore—

$$\propto R \times N_1 \times \frac{t}{t-x},$$

and that between C and D—

$$\propto R \times N_1 \times \frac{t}{x}.$$

The size of the flux a passing between B C is therefore—

$$a = \frac{\overline{BC}}{R \times N_1 \times \frac{t}{t-x}} = \frac{2C}{R \times N_1^2 \times t^2}(xt - t^2) \quad . \quad . \quad . \quad . \quad (14)$$

and the flux a' passing between C and D may be found to be—

$$a' = \frac{\overline{CD}}{R \times N_1 \times \frac{t}{x}} = \frac{2C}{R \times N_1^2 \times t^2}(xt - t^2) \quad . \quad . \quad . \quad . \quad (15)$$

Both of these fluxes are shown in Fig. 3(c) in somewhat larger scale.

We see that $a = -a'$. This, of course, must be the case, since, according to our previous considerations, the flux in the tooth 1′ must be zero, while the currents in both members are active. If the same investigation is repeated all round the air-gap it will be found that there are altogether four fields—a, b, c, and d—of equal size flowing These fields are indicated by dotted lines in Fig. 4.

In order to show how these fields are located in relation to the windings of the two phases, the conductors of the two phases are

marked differently (Fig. 4). The fields a and c are of equal phase, while the fields b and d are shifted 90° against a and b.

The average values of the leakage fluxes for various rotor positions, that is various values of x, follows from the simple integration—

$$a_{\text{average}} = \frac{2\,C}{R \times N_1^2 \times t^3}\int_0^t (x\,t - x^2)\,d\,x = \frac{2\,C}{R \times N_1^2 \times t^3}\left(\frac{t^3}{2} - \frac{t^3}{3}\right)$$

$$= \frac{C}{3 \times N_1^2 \times R} \quad \ldots\ldots\ldots \quad (16)$$

The maximum value for a occurs when $x = \frac{t}{2}$, and is—

$$a_{\text{max.}} = \frac{C}{2 \times N_1^2 \times R} \quad \ldots\ldots\ldots \quad (17)$$

The potentials induced by the fluxes a, b, c, and d, are, of course, proportional to the fluxes and to the number of turns per coil, and lag 90° behind the fluxes. These potentials are shown for the various stator coils in Fig. 3(d).

The resultant vector of this figure represents the potential e_z, while the corresponding vector of Fig. 4 of the previous paper * represents the potential e_m.

Since in the case under consideration the two equal fields a and c interlink with all the turns w of one phase, the potential induced by the zigzag fluxes is—

$$e_z \propto 2\,a\,w = \frac{2\,C\,w}{3 \times N_1^2 \times R} \quad \ldots\ldots\ldots \quad (18)$$

and the zigzag leakage coefficient follows to be—

$$\sigma_z = \frac{e_z}{e_m} = \frac{4}{3\,N_1^2\,k} \quad \ldots\ldots\ldots \quad (19)$$

(b) *Three-phase.*—After having treated the 2-phase case much in detail, the full-pitch 3-phase case may be disposed of very briefly. We find in this case, again, one flux going round each phase belt, only we obtain six different fluxes, since there are six phase belts.

The following value for the zigzag leakage coefficient is obtained:—

$$\sigma_z = \frac{e_z}{e_m} = \frac{3}{2\,N^2\,k} \quad \ldots\ldots\ldots \quad (20)$$

2. *Open Slots and Full-pitch Windings—Number of Slots the Same in Both Members.*—While it has been found advisable to deal in the previous paragraph with the ideal case of an entirely closed slot, in order better to bring out the simplicity of the fundamental phenomena of the zigzag leakage, we will now deal with the influence of the slot

* *Transactions of the American Institute of Electrical Engineers*, vol. 27, p. 1377, 1908.

openings. The dispersion of the fluxes must, of course, be taken into consideration.

It appears from Fig. 4 that the zigzag flux is going always from the edge of a certain tooth of one member to the other member, and from there back to the adjacent edge of the next tooth of the first member. We may thus consider two adjacent teeth as poles of opposite polarity, and may find the effective tooth width from the lower curve of Fig. 15 when considering the zigzag fluxes. Assuming at the present that the effective dimensions given in Fig. 1 are found this way, the said figure may serve also for the consideration of the zigzag leakage. It appears at once that zigzag fluxes are only possible while the rotor occupies positions between that of Fig. 1, D and F. We may also use the diagrams of Fig. 3 for the present considerations, since nothing but the reluctance has changed, and therefore the scale for the flux vectors has changed. If this difference is taken properly into consideration, and the further derivations are carried through in a way similar to the one previously outlined for entirely closed slots, we obtain the following results :—

$$e_z \propto \frac{a_2 - b_1}{t} \times \frac{2\,C\,w}{3\,N_1^2 R} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (21)$$

and—

$$\sigma_z = \frac{e_z}{e_m} = G \times \frac{a_2 - b_1}{t} \times \frac{4}{3\,N_1^2 k} = G\,(c_1 + c_2 - 1) \times \frac{4}{3\,N_1^2 k} \qquad (22)$$

The effect of the slot opening in 3-phase motors is, of course, the same as in 2-phase motors.

The influence of the size of the slot openings upon the zigzag leakage coefficient may be seen from Fig. 19. The value for entirely closed slots has been assumed in this curve to be one; four curves for different air-gaps have been figured from the above formula and plotted in terms of the primary slot opening. These curves show that the zigzag leakage coefficient decreases as the slot opening increases. It should not be concluded from this, however, that a wide slot opening is desirable. Most of the other parts of the total leakage coefficient increase with the size of the slot openings within the customary limits, and their increase more than counterbalances the decrease of the zigzag coefficient.

3. *Entirely Closed Slots and Fractional Pitch Winding—Number of Slots the Same in Both Members.*—(*a*) *Two-phase Motors :* It is at once obvious that the influence of the slot openings and the rotor position is for this case the same as for the 2-phase full-pitch windings. It will therefore be sufficient to investigate here the magnetomotive forces and fluxes. As instance for the derivation we may choose again a 2-phase winding with 8 slots per pole, but a pitch of 135 electrical degrees, as shown in Fig. 5(*a*). A diagram representing the magnetomotive forces in the primary teeth is reproduced in Fig. 5(*b*) from Fig. 21 of the previous paper. If we determine in this diagram, as previously done in Fig. 3(*b*), the fluxes entering, for instance, the secondary tooth 7′,

we obtain again, as before, a flux c which is of the same size and amplitude as the flux a found before for tooth $1'$ in case of the full-pitch winding. If we investigate, however, tooth $5'$ in the same manner, we find a flux f, which is shifted 45° and in size only $= \sqrt{2}\,c$. After determining the fluxes all around the pole-face, we obtain altogether eight fluxes, a, b, c, d, e, f, g, and h, as shown in Figs. 5(c) and 6. In order to show the relation between the windings of the two phases and the

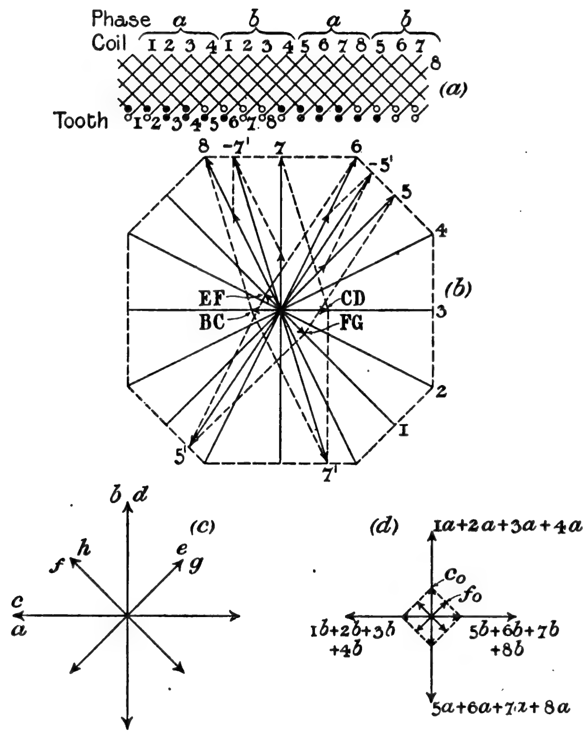

FIG. 5.

fluxes, the conductors of the two phases are again marked different The potentials induced are now easily found. The flux c, for instance, induces in the coils—see Fig. 5(d)—$3a$ and $4a$ a potential $c_0 = \frac{w}{4} c$; the flux f induces in the coils $1a$ and $2a$ a potential $f_0 = \frac{w}{4} f$, etc.

By adding all the potentials induced in one phase we obtain the total potential e_x induced per phase. We may derive, however, more directly as follows: It appears directly from Fig. 6 that the fluxes a

and c interlink with $\frac{w}{2}$ turns of phase a, and therefore induce a potential proportional to $\frac{w}{2}(a+c)$. The fluxes e, f, g, and h interlink each with $\frac{w}{4}$ turns of phase a, and induce potentials proportional to $\frac{w}{4}e$, $\frac{w}{4}f$, etc.

Since these potentials are equal in size and shifted 90° against each

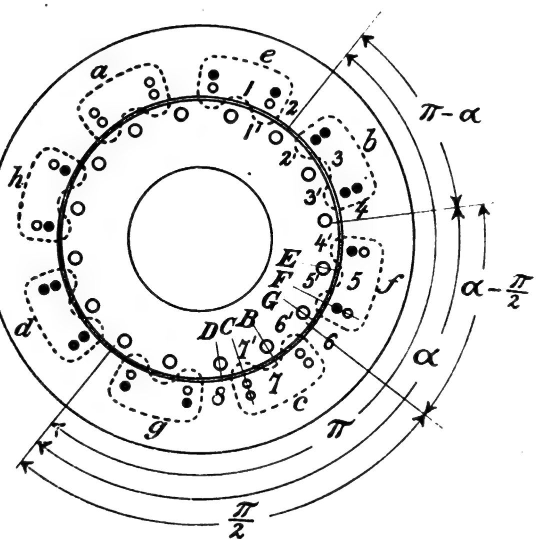

FIG. 6.

other, each two of them combine to a resultant potential $\propto \sqrt{2}\frac{w}{4}e$, and the total potential induced per phase follows to be—

$$e_x = \frac{w}{2}(a+c) + \sqrt{2}\frac{w}{2}e.$$

Similar results will be obtained for any coil-pitch between 90 and 180 electrical degrees. There will be always eight fluxes. The fluxes a, b, c, and d surround those slots which contain conductors of one phase only, while the fluxes e, f, g, and h surround those slots which contain conductors of both phases. Since the fluxes e, f, g, and h are 45° shifted against the fluxes a, b, c, and d, and since e and g and f and h are 90° apart respectively, it appears at once that the resultant effect of each of the two fluxes e and g and f and h upon the phase a, for instance, is proportional to $\frac{1}{\sqrt{2}}e$, $\frac{1}{\sqrt{2}}f$, $\frac{1}{\sqrt{2}}g$, and $\frac{1}{\sqrt{2}}h$ respectively

The number of turns surrounded by any of the fluxes is also easily determined. If a is the angle of the coil-pitch, the phases overlap $(\pi - a)$ degrees, while each individual phase alone is active over $\left(a - \frac{\pi}{2}\right)$ degrees. Since the total turns of one phase fill the slots over $\frac{\pi}{2}$ circumference, the turns surrounded by one of the fluxes a, b, c, and d are $= \frac{2w}{\pi}\left(a - \frac{\pi}{2}\right)$, and the total turns surrounded by one of the fluxes $e, f, g, h = \frac{w}{2}(\pi - a)$.

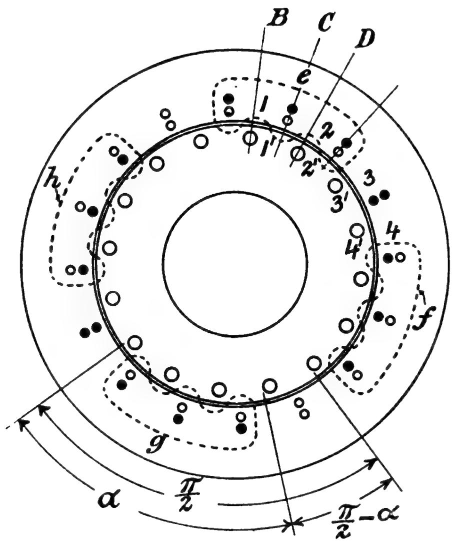

FIG. 7.

The resultant potential induced per phase is therefore—

$$e_z \propto \frac{2w}{\pi}\left(a - \frac{\pi}{2}\right)(a + c) + \frac{1}{\sqrt{2}}\frac{w}{\pi}(\pi - a)(e + f + g + h),$$

or, since it appears at once from Fig. 6 that—

$$a = c \text{ and } e = f = g = h = \frac{a}{\sqrt{2}},$$

we obtain—

$$e_z = \frac{a}{\pi} \times 4wa \quad \ldots \ldots \ldots \quad (23)$$

If we introduce now the air-gap reluctance, etc., as previously done, for the full-pitch winding, we obtain—

$$e_z = \frac{a}{\pi} \frac{(a_1 - b_2)}{t} \frac{4\,C}{3\,N_1^2\,R} \quad \ldots \quad (24)$$

and the zigzag leakage coefficient follows to be—

$$\sigma_z = \frac{a}{\pi \sin^2 \frac{a}{2}} G\,(c_1 + c_2 - 1) \frac{4}{3\,N_1^2\,k} \quad \ldots \quad (25)$$

In this formula the first member considers the influence of the fractional pitch, the second the influence of the slot openings, and the third member is the value found for full-pitch windings and entirely closed slots.

Conditions for pitches of less than 90° are somewhat different. We obtain in this case only the fluxes e, f, g, and h, as indicated in Fig. 7.

Proceeding, however, in a similar way as outlined for the previous case, we obtain the same expression for σ_z as given in formula (25). This value applies, therefore, for all 2-phase primary windings in combination with a squirrel-cage secondary of an equal number of slots.

(*b*) *Three-phase.*—For 3-phase fractional pitch windings conditions are in principle as simple as for 2-phase. Conditions are different from the 2-phase case only in so far as we have to distinguish between three different possible conditions, and, in contradistinction to the 2-phase case, they lead to three different expressions, which are as follows:—

1. For pole-pitches between π and $\frac{2}{3}\pi$—

$$\sigma_z = \frac{\pi + 3\,a}{4\,\pi\,c} G\,(c_1 + c_2 - 1) \frac{1{\cdot}5}{N_1^2\,k} \quad \ldots \quad (26)$$

2. For pole-pitches between $\frac{2}{3}\pi$ and $\frac{1}{3}\pi$—

$$\sigma_z = \frac{6\,a - \pi}{4\,\pi\,c} G\,(c_1 + c_2 - 1) \frac{1{\cdot}5}{N_1^2\,k} \quad \ldots \quad (27)$$

3. For pole-pitches between $\frac{1}{3}\pi$ and o—

$$\sigma_z = \frac{3\,a}{4\,\pi\,c} G\,(c_1 + c_2 - 1) \frac{1{\cdot}5}{N_1^2\,k} \quad \ldots \quad (28)$$

(*c*) *Comparative Notes.*—The relative merits of 2- and 3-phase windings and the various possible coil-pitches appear at once from Fig. 17. The curves shown there give the relative values of the leakage coefficients for any number of slots for 2- and 3-phase windings in terms of the coil-pitch as obtained from the above formulæ. Since most of the other parts of the leakage coefficient are similarly affected by the number of phases and the coil-pitch, these curves are a pretty good criterion for the cases covered by them.

4. *Entirely Closed Slots and Full-pitch Winding—Number of Primary Slots larger than Number of Secondary Slots.*—In the previous paragraphs the zigzag leakage for an equal number of slots in both members has been considered much in detail, for the reason that this case gives the clearest conception of the phenomena. In practice the number of slots are, however, different from each other, and it remains to investigate this more general case.

Let us consider first the case in which the secondary number of slots is smaller than the number of slots in the primary. The various

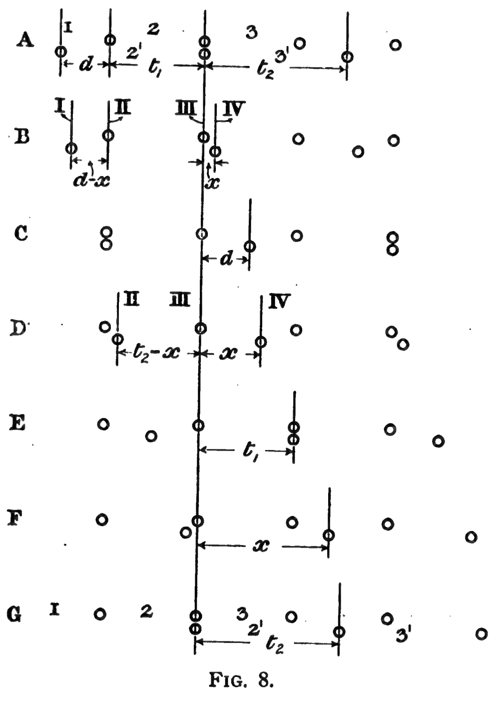

FIG. 8.

possible relative locations of the primary and secondary slots are shown for such a case in Fig. 8.

It appears at once from this figure that two distinctly different conditions are possible in the case under consideration.

1. While the rotor is in positions between A and C the rotor tooth 2′ is under the influence of three stator teeth—*i.e.*, the teeth 1, 2, and 3. The same condition ex'sts while the rotor is in positions between E and G.
2. While the rotor is in position between C and E the same rotor tooth 2′ is under the influence of the two stator teeth 2 and 3 only.

The first condition may be considered separately—for instance, under the assumption of a 2-phase motor wound full pitch. Fig. 9(*a*) may represent for such a motor a segment of the diagram of the primary tooth fluxes, and the vectors 1, 2, and 3 may be assumed to represent the fluxes of the primary teeth 1, 2, and 3 of Fig. 8, while there is no secondary reaction. The total flux, which enters the secondary tooth 2′, in this case may be found by simply combining the vector $p_1 = \bar{1}\,\frac{d-x}{t_1}$, the vector $\bar{2}$, and the vector $p_3 = \bar{3}\,\frac{x}{t_1}$ to the resultant vector $\overline{-2'}$. Then we find equal and opposite to $\overline{-2'}$ the vector $\overline{2'}$, which represents the flux leaving the tooth 2′, under the assumption that the secondary currents are acting alone.

If we assume now the scale of the magnetomotive forces to be such that the vectors $\bar{1}$, $\bar{2}$, and $\bar{3}$ may also be considered to represent the magnetomotive forces of the teeth 1, 2, and 3, we find the vector for the magnetomotive force of the secondary tooth 2′ to be—

$$\overline{2'_m} = \frac{\overline{2'}\,t_1}{t_2}.$$

We find now the following resultant magnetomotive forces acting upon the various portion of the air-gap :—

1. Between I. and II. (Fig. 8, position B) the resultant $\overline{\text{I.–II.}}$ of the vectors $\bar{1}$ and $\overline{2'_m}$ (Fig. 9A).
2. Between II. and III. the resultant $\overline{\text{II.–III.}}$ of the vectors $\bar{2}$ and $\overline{2'_m}$.
3. Between III. and IV. the resultant $\overline{\text{III.–IV.}}$ of the vectors $\bar{3}$ and $\overline{2'_m}$.

The size of the vectors follows from a simple geometrical calculation based upon Fig. 9A, if we remember that the distances 1–2 and 2–3 have been previously found to be proportional to $\frac{2\,C}{N_1}$.

We find—

$$\overline{\text{I.–II.}} = \frac{2\,C}{N_1}\left(1 - \frac{1}{t_2}(d - 2x)\right).$$

$$\overline{\text{II.–III.}} = \frac{2\,C}{N_1}\,\frac{1}{t_2}(d - 2x).$$

$$\overline{\text{III.–IV.}} = \frac{2\,C}{N_1}\left(1 - \frac{1}{t_2}(d - 2x)\right).$$

The reluctances are as follows :—

1. Between I. and II. proportional to $R\,N_1\,\frac{t_1}{d-x}$.
2. Between II. and III. proportional to $R\,N_1$.
3. Between III. and IV. proportional to $R\,N_1\,\frac{t_1}{x}$.

From the above magnetomotive forces and reluctances the fluxes follow directly. The flux between III. and IV. is, for instance—

$$c = \frac{2\,C\,x}{R\,N_1^2\,t_1}\left(1 - \frac{1}{t_2}(d - 2\,x)\right).$$

Similarly may be found the fluxes a and b. In order to show the relative size of the three fluxes they are shown in a larger scale in Fig. 9B.

In accordance with our previous assumption, we find again that the total flux a entering the top of tooth $2'$ equals to the total flux $b + c$ returning from this tooth to the stator. The flux values found above apply for all rotor positions, for which x is of value between 0 and $t_2 - t_1 = d$.

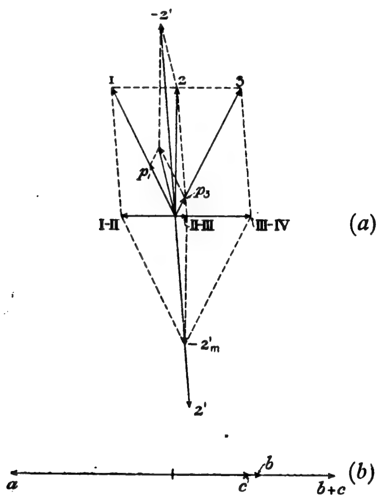

FIG. 9.

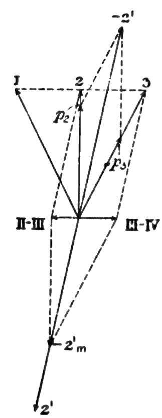

FIG. 10.

It remains to investigate now the fluxes for the rotor positions, for which x assumes values between d and t_2 (see Fig. 8, position C to E).

We start out again with the fluxes $\bar{1}$, $\bar{2}$, and $\bar{3}$ in Fig. 10.

The total flux entering the secondary tooth $2'$, while there is no current in the secondary flowing, is the resultant $\overline{-2'}$ of the vectors—

$$p_2 = \bar{2}\,\frac{t_2 - x}{t_1} \text{ and } p_3 = \bar{3}\,\frac{x}{t_1}.$$

The further derivation of the diagram is obvious from Fig. 10 and the previous case. We find the flux—

$$c = \frac{2\,C}{R\,N_1^2\,t_1}\left(x - \frac{1}{t_2}\,x^2\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (29)$$

While the rotor is in positions between position E and G, shown in Fig. 8, conditions are the same as for the positions between position A and C. These positions may therefore be taken into account by simply doubling the expression found for the first condition. The average value for the flux c follows now from the following integration—

$$c_{\text{average}} = \frac{2\,C}{R\,N_1^2\,t_1\,t_2}\left\{2\int_0^d\left[x\left(1-\frac{1}{t_2}d\right)-\frac{2}{t_2}x^2\right]dx+\int_d^{t_1}\left(x-\frac{1}{t_2}x_2\right)dx\right\}$$

$$c_{\text{average}} = \frac{3\,t_2^3-6\,t_1\,t_2^2+6\,t_1^2\,t_2-2}{t_1\,t_2^2}\;\frac{C}{3\,R\,N_1^2} \quad \ldots\ldots\ldots\ldots \quad (30)$$

If now—

$$\frac{N_1}{N_2} = K \text{ and therefore } t_2 = K\,t_1,$$

we get—

$$c_{\text{average}} = \frac{C}{3\,N_1^2\,R}\;\frac{3\,K^3-6\,K^2+6\,K-2}{K^2} \quad \ldots\ldots \quad (31)$$

and—

$$\sigma_z = \frac{4}{3\,N_1^2\,k}\;\frac{3\,K^3-6\,K^2+6\,K-2}{K^2} \quad \ldots\ldots \quad (32)$$

It should be noticed that the first of the two factors of this expression is the same as found for an equal number of slots, and that therefore the second factor takes the influence of the decreased number of secondary slots into account.

The last few equations have a rather complicated appearance. This, however, should not be laid against the graphical method. It should be borne in mind that this method has given for the above derivation a clear picture (see Figs. 9 and 10) of the conditions for each of the possible positions of the rotor tooth, and has made it possible to study the complicated phenomena in a fairly simple manner. The fact that the fundamental conditions change materially, while the secondary slots occupy the various possible positions, and that therefore the different conditions have to be considered separately cannot be helped by any method. It is on account of this fact that the determination of the average value [formula (30)] calls of necessity for the integration of several separate members.

5. *Entirely Closed Slots and Full-pitch Winding—The number of Primary Slots is smaller than the Number of the Secondary Slots.*—In this case each secondary tooth is never under the influence of more than two primary teeth, as will be seen from Fig. 11. The fluxes impressed upon the secondary tooth 1′ are, while there are no secondary currents flowing (see Fig. 12)—

$$p_1 = \bar{1}\,\frac{t_2-x}{t_1} \text{ and } p_2 = \bar{2}\,\frac{x}{t_1}\,.$$

By further proceeding as outlined in the previous cases we obtain—

$$\sigma_z = \frac{4}{3\,N_1^2\,k}\,K = \frac{4}{3\,N_1\,N_2\,k} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (33)$$

6. *Open Slots and Full-pitch Windings—Number of Primary Slots is different from the Number of Secondary Slots.*—The influence of an unequal number of primary and secondary number of slots is in case of open slots somewhat different from what has previously been found for closed slots. A number of different conditions depending upon the relative size of primary and secondary slot openings and tooth-pitch are possible. The investigation of these various cases naturally leads to formulæ which are too elaborate to be of great practical value. Since, moreover, each particular case may be easily considered in a

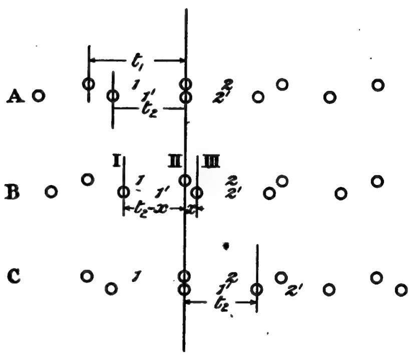

FIG. 11.

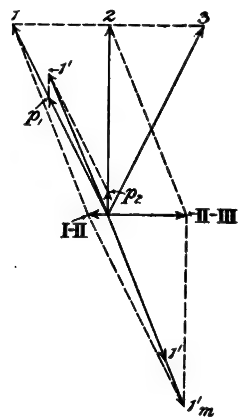

FIG. 12.

manner quite similar to that outlined before, the investigations for these cases may be omitted.

7. *Fractional Pitch Windings—Number of Primary Slots is different from the Number of Secondary Slots.*—The magnetomotive forces of the zigzag leakage are, of course, independent of the secondary number of slots. Consequently the influence of fractional pitch windings in the primary may be taken into account by the factors determined for an equal number of slots in both members, no matter what is the ratio between primary and secondary number of slots.

SLOT AND LEAKAGE.

After having treated the zigzag leakage much in detail, the primary slot leakage may be disposed of very briefly, since it is in its general characteristics very similar to the zigzag leakage. Let us again start out from a full-pitch 2-phase winding as shown in Fig. 3(*a*). The diagram for the magnetomotive forces in the primary teeth is reproduced

in Fig. 13. The magnetomotive force across each slot may be found therefrom by simply subtracting the magnetomotive forces of the adjacent teeth from each other. Thus the magnetomotive force $\overline{1-2}$ across the slot between the teeth 1 and 2 may be found by adding to

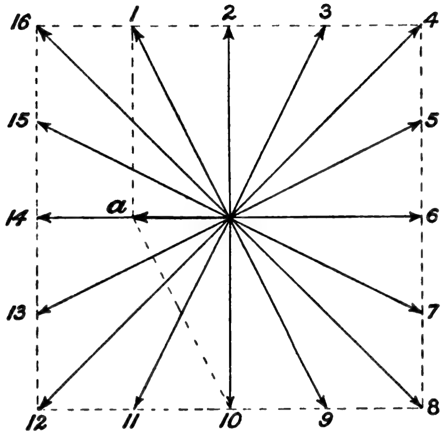

FIG. 13.

the vector $\bar{1}$ a vector which is equal and opposite to the vector $\bar{2}$. We see that the vectors $\overline{1-2}$ equals one of the divisions of the square diagram for the magnetomotive forces, that is, it is proportional to $\frac{2C}{N_1}$.

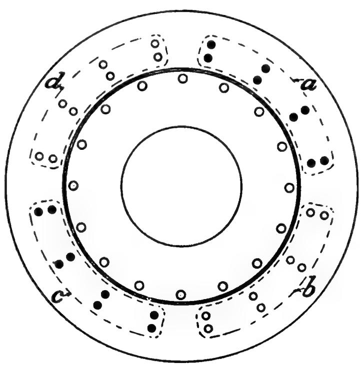

FIG. 14.

The flux a across the slot is therefore proportional to $\frac{2C}{N_1 R_s}$, if R_s is the reluctance across the slot. By investigating the fluxes for the other slots we find again four fluxes, a, b, c, and d (see Fig. 14), as in case of

the zigzag leakage (compare Fig. 4). The zigzag and slot leakage fluxes are only different in so far as the former pass through the air-gap and the top of a secondary tooth from one primary tooth to another, while the latter pass directly across the slot from one tooth to the other. The effects of the two fluxes are therefore very much alike.

We find the potential induced by the slot fluxes in one of the phases proportional to—

$$e_s = \frac{4\,C\,w}{N_1\,R_s},$$

and the slot leakage coefficient follows to be—

$$\sigma_{1s} = \frac{8\,R\,G}{N_1\,R_s\,k} \quad \ldots\ldots\ldots\ldots \quad (34)$$

It is customary to introduce instead of R_s the so-called slot constant—

$$s_1 \propto \frac{L}{R_s} \quad \ldots\ldots\ldots\ldots \quad (35)$$

where L is the width of core of the motor. We may, moreover, introduce—

$$R \propto \frac{g}{\tau\,L} \quad \ldots\ldots\ldots\ldots \quad (36)$$

and obtain—

$$\sigma_{1s} = \frac{8\,g\,S_1\,G}{N_1\,\tau\,k} \text{ for 2-phase machines} \quad \ldots\ldots \quad (37)$$

Similarly we obtain—

$$\sigma_{1s} = \frac{9\,g\,S_1\,G}{N_1\,\tau\,k} \text{ for 3-phase machines} \quad \ldots\ldots \quad (38)$$

where g = air-gap on one rotor side and τ = pole-pitch.

In case of fractional pitch windings distinction should be made between slot fluxes which interlink with all conductors in one slot and fluxes which interlink only with part of the conductors. The latter are more or less out of phase with the former, and for the derivation of an exact formula this should be taken into consideration. In practice the influence of fluxes which interlink only with part of the conductors of one slot is comparatively small, and the error introduced by assuming that they have the same phase as the fluxes interlinking with all the conductors of one phase is therefore negligible for all pitches which are generally used in practice, excepting possibly cases where the number of slots per pole is exceptionally small.

Assuming that the above approximation is justified, it is at once obvious that the effect of reducing the winding-pitch must be in the case of the slot leakage the same as in the case of the zigzag leakage; therefore the factors previously determined for the zigzag leakage may be used also for an approximate calculation of the slot leakage.

Although it has been found inadvisable to give in the present paper a complete analysis of the leakage phenomena, it has been sufficiently

demonstrated that the graphical method lends itself readily for the investigation of almost every problem arising in connection with the study of the leakage fields. The only exception is the end-connection leakage, which therefore has been omitted from the main body of this paper. The Appendix gives, however, a formula for the same, which has been found sufficiently exact for practical use. Since the so-called belt or differential fluxes are frequently classed among the leakage fluxes on account of the fact that they influence the performance of the motor in a way very similar to that of the leakage fluxes, the author has given also a short formula for the determination of these fluxes in the Appendix.*

APPENDIX.

1. Primary Zigzag Leakage.

The primary zigzag leakage coefficient of a squirrel-cage motor may be quite generally expressed by the following formula—

$$\sigma_z = \frac{k_s k_0 k_t k_p}{N_1^2 k} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (39)$$

where—

N_1 is the number of slots per pole in the primary.
k_s a coefficient depending upon the ratio of the number of secondary slots to the number of primary slots.
k_0 a coefficient depending upon the size of the slot openings.
k_t a coefficient depending upon the throw of the primary coils.
k_p a coefficient depending upon the number of phases in the primary.
k a coefficient depending upon the number of slots *and the number of phases in the primary.*

We have found for entirely closed slots—

$$k_s = \frac{3\,K^3 - 6\,K^2 + 6\,K - 2}{K^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (40)$$

for—

$$\frac{N_1}{N_2} = K > 1 \text{ [compare formula (32)]},$$

and—

$$k_s = K \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (41)$$

for—

$$\frac{N_1}{N_2} = K < 1 \text{ [compare formula (33)]}.$$

N_2 is the number of slots per pole in the secondary.

* A short qualitative treatment of the belt or differential fluxes is given in *Electrical Review and Western Electrician*, vol. 54, p. 32, 1909. The derivation of the formula given for the differential fluxes is given in *Elektrotechnische Zeitschrift*, vol. 30, p. 841, 1909.

These values apply also approximately for open slots. The values of k_s are given for all practical values of $\frac{1}{K} = \frac{N_2}{N_1}$ by curve A in Fig. 16.

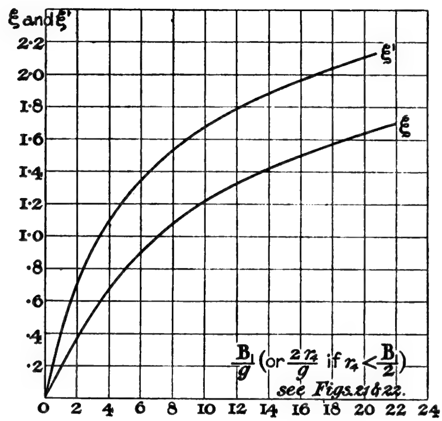

Fig. 15.

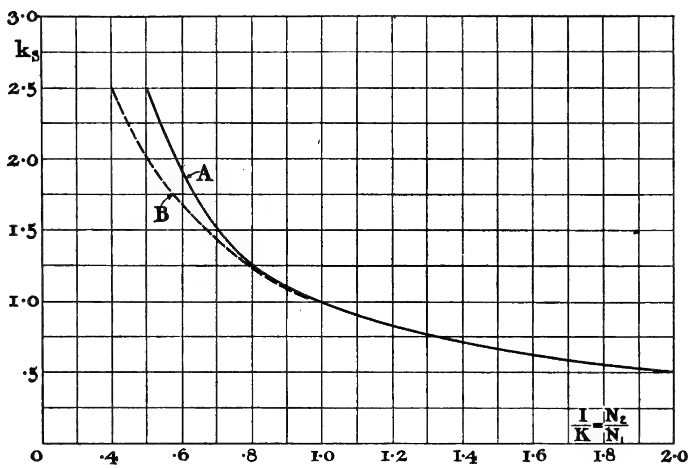

Fig. 16.

The value of k_0 for an equal number of slots in primary and secondary has been found to be—

$$k_0 = G(c + c_2 - 1) \text{ [compare formula (22)]} \quad . \quad . \quad (42)$$

where—

$$\left.\begin{aligned} c_1 &= \frac{a_1}{t_1} = \frac{A_1 + 2\,\xi_1\,g}{t_1} \\ c_2 &= \frac{a_2}{t_2} = \frac{A_2 + 2\,\xi_2\,g}{t_2} \end{aligned}\right\} \quad \ldots \ldots \ldots \quad (43)$$

$$G = \frac{1}{c'_1 \times c'_2} \quad \ldots \ldots \ldots \ldots \quad (44)$$

g = air-gap clearance on one side of the rotor.
A_1 = width of primary tooth top.
A_2 = width of secondary tooth top.
ξ_1 is found from the lower curve of Fig. 15 for $\frac{B_1}{g}$.
ξ_2 is found from the lower curve of Fig. 15 for $\frac{B_2}{g}$.
B_1 = width of primary slot opening.
B_2 = width of secondary slot opening.

The values for c'_1 and c'_2 are found from the same formulæ as c_1 and c_2, except that the values ξ_1 and ξ_2 are replaced by the values ξ'_1 and ξ'_2, which are found from the upper curve of Fig. 15.

The above formula for determining k_e will also give practically correct values, when the number of secondary slots is different from the number of primary slots, and the difference is within the usual practical limits.

The value for k_t may be found from the following formulæ :—

(*a*) *Two-phase Windings.*

$$k_t = \frac{a}{\pi \sin^2 \frac{a}{2}} \text{ [compare formula (25)]} \quad \ldots \quad (45)$$

(*b*) *Three-phase Windings.*

$$k_t = \frac{\pi + 3\,a}{4\,\pi \sin^2 \frac{a}{2}} \text{ for } a = \frac{2}{3}\,\pi \text{ to } \pi \quad \ldots \ldots \quad (46)$$

$$k_t = \frac{6\,a - \pi}{4\,\pi \sin^2 \frac{a}{2}} \text{ for } a = \frac{1}{3}\,\pi \text{ to } \frac{2}{3}\,\pi \quad \ldots \ldots \quad (47)$$

$$k_t = \frac{3\,a}{4\,\pi \sin^2 \frac{a}{2}} \text{ for } a = 0 \text{ to } \frac{1}{3}\,\pi \quad \ldots \ldots \quad (48)$$

[Compare formulæ (26), (27), and (28).]

a = the angle of the coil throw (pitch) in electrical degrees, and may be found from—

$$a = \frac{N_t}{N_1}\,180^\circ \quad \ldots \ldots \ldots \ldots \quad (49)$$

N_t = the number of teeth surrounded by each primary coil.

The values for k_t are given by the curves of Fig. 17, and may be taken directly from said curves.

The value of k_p has been found to be—

$$k_p = \frac{4}{3} = 1{\cdot}333 \text{ for 2-phase windings [compare formula (19)],}$$

and—

$$k_p = \frac{3}{2} = 1{\cdot}500 \text{ for 3-phase windings [compare formula (20)].}$$

The values for k may be found from the curves of Fig. 18, which is reproduced from Fig. 15 of the previous paper.*

The calculation of the zigzag leakage is now reduced to the multiplication of a number of coefficients, which, with the exception of the coefficient k_o, may be taken directly from curves.

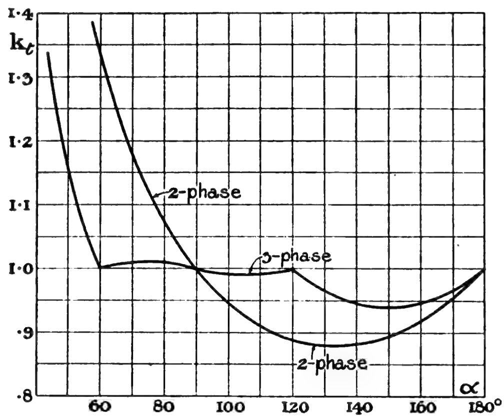

FIG. 17.

Since, in practice, the slot openings of the secondary and the slot-pitch vary comparatively little, approximate values for k_o may be found from the curves of Fig. 19.

The curves given there are all figured for a secondary slot opening $= 15\ t$. A change of this dimension within the customary limits does not affect the results, however, to any appreciable amount.

Further simplifications may be obtained as follows: If we introduce for k_s for values of $\frac{N_2}{N_1} < 1$ the same expression as found for $\frac{N_2}{N_1} > 1$, we obtain values as shown by the dotted line B in Fig. 16.

It will be seen that for all practical values of the slot ratio this dotted line is not very far distant from the exact line, and it seems

* *Transactions of the American Institute of Electrical Engineers*, vol. 27, p. 1387, 1908

therefore justifiable to use for standard cases the simple expression found for $\frac{N_2}{N_1} > 1$ for cases where $\frac{N_2}{N_1}$ is smaller than 1 also.

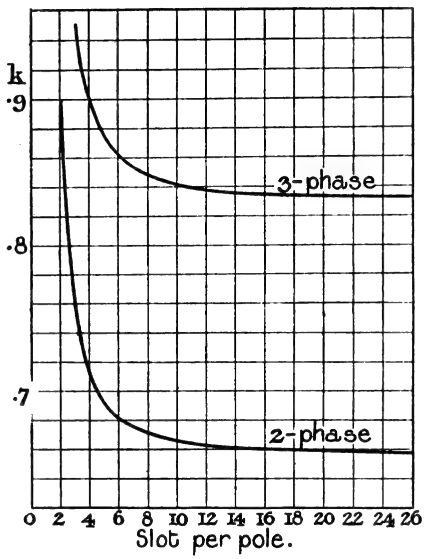

FIG. 18.

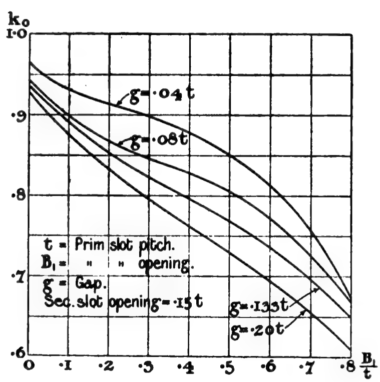

FIG. 19.

We may then omit the coefficient k_s entirely by introducing for N_1^2 the product $N_1 N_2$. The formula for the primary zigzag leakage coefficient reads, then, as follows :—

$$\sigma_z = \frac{k_0 k_t k_p}{N_1 N_2 k} \quad \ldots \ldots \ldots \quad (50)$$

2. Secondary Zigzag Leakage.

It follows from the consideration of this paper that a secondary zigzag leakage does not exist in case of a squirrel-cage rotor of zero resistance. The test in practice cannot be made, however, for this ideal condition, and it may be shown that when the secondary number of slots is larger than the primary, certain secondary zigzag fluxes are possible when the secondary resistance is different from zero. These fluxes are, however, very small, and will, in most cases, be sufficiently taken into account by slightly increasing the value found for the primary leakage.

If we introduce an allowance factor $k_a = 1{\cdot}05$ into the formula for the primary zigzag leakage, the same will, for cases where $N_2 > N_1$, take the influence of secondary zigzag fluxes, which may affect the actual test results sufficiently into account; for cases where $N_2 < N_1$, the allowance coefficient will take care of the fact that the actual values for k_s are slightly larger than obtained from formula (50) (see Fig. 16).

3. Total Zigzag Leakage.

The total zigzag leakage coefficient may therefore be found from—

$$\sigma_z = \frac{k_a k_0 k_t k_p}{N_1 N_2 k} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (51)$$

From Fig. 18 it will be seen that the coefficient k is practically constant for all customary numbers of slots per pole; the error introduced by setting—

$$k = 0{\cdot}665 \text{ for 2-phase,*}$$
$$k = 0{\cdot}838 \text{ for 3-phase,}$$

is very small.

We may now combine the four coefficients, k_a, k_t, k_p, and k, into one—

$$K_z = \frac{k_a k_t k_p}{k},$$

the values for which may be found from Fig. 20.

The total zigzag leakage coefficient is then—

$$\sigma_z = \frac{k_0 K_z}{N_1 N_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (52)$$

This formula is very simple and practically correct; its use in practice may therefore be recommended.

For less correct calculations we may set—

$k_0 = 0{\cdot}92$ for partially closed slots in both members.
$k_0 = 0{\cdot}85$ for partially closed slots in the rotor and open slots in the stator.
$K_z = 2{\cdot}00$ for 2-phase windings.
$K_z = 1{\cdot}83$ for 3-phase windings (see Fig. 20).

* See *Electrical World*, vol. 52, p. 1343, 1908.

We obtain, then, the following approximate formulæ, for which no curves are required :—

$$\sigma_x = \frac{1}{N_1 N_2} \left\{ \begin{array}{l} \text{for 2-phase, partially closed slots in} \\ \quad \text{both members} \end{array} \right\} \quad . \quad . \quad . \quad . \quad (53)$$

$$\sigma_x = \frac{1{\cdot}70}{N_1 N_2} \left\{ \begin{array}{l} \text{for 3-phase, partially closed slots in} \\ \quad \text{both members} \end{array} \right\} \quad . \quad . \quad . \quad . \quad (54)$$

$$\sigma_x = \frac{1{\cdot}70}{N_1 N_2} \left\{ \begin{array}{l} \text{for 2-phase, partially closed slots in} \\ \quad \text{rotor, and open slots in stator} \end{array} \right\} \quad . \quad . \quad . \quad . \quad (55)$$

$$\sigma_x = \frac{1{\cdot}55}{N_1 N_2} \left\{ \begin{array}{l} \text{for 3-phase, partially closed slots in} \\ \quad \text{rotor, and open slots in stator} \end{array} \right\} \quad . \quad . \quad . \quad . \quad (56)$$

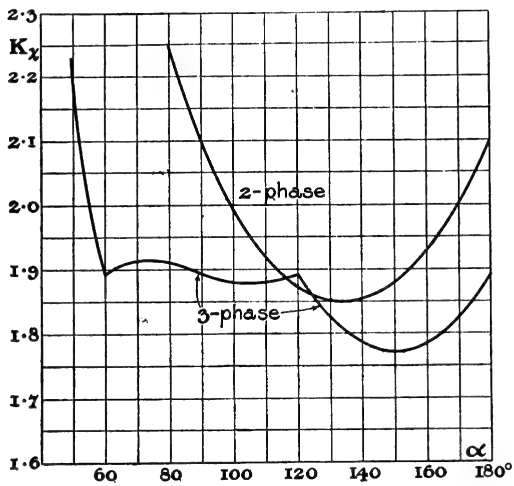

FIG. 20.

The zigzag leakage in motors with a wound secondary is slightly different from that of a squirrel-cage motor. The above formulæ are, however, for practical purposes, close enough for the wound secondary case also.

The above formulæ have been derived for windings with two coils per slot. They will also apply for full-pitch windings with one coil per slot. For fractional pitch windings with one coil per slot the leakage will be larger. This is on account of the fact that with the reduction of the pitch the effect of the main flux decreases proportional to—

$$\frac{1}{\sin^2 \frac{\alpha}{2}},$$

while the zigzag fluxes do not decrease at all. For these cases the zigzag leakage coefficient may therefore be found by figuring it from the above formulæ for full pitch, and multiply these values with—

$$\frac{1}{\sin^2 \frac{\alpha}{2}}.$$

4. Primary Slot Leakage.

The primary slot leakage coefficient may be expressed by the following formula :—

$$\sigma_{1s} = \frac{k_t k_p g G S_1}{N_1 k \tau} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (57)$$

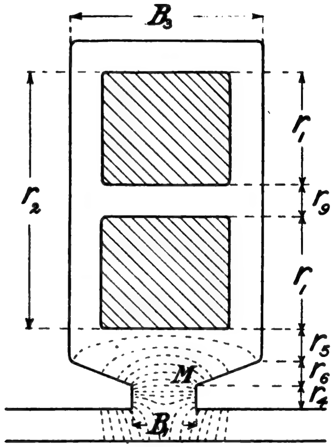

Fig. 21.

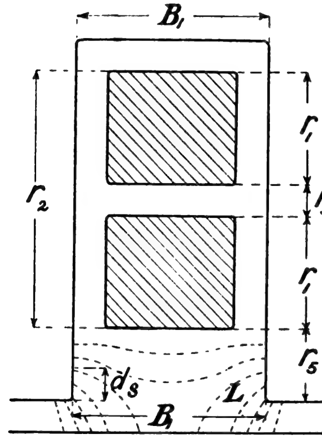

Fig. 22.

where—

k_t = a coefficient depending upon the coil-pitch [see formula (45) to (49) and Fig. 17].

k_p = a coefficient depending upon the number of phases.

We found—

k_p = 8 for 2-phase windings [compare formula (37)].

k_p = 9 for 3-phase windings [compare formula (38)].

k = a coefficient depending upon the number of slots per pole and the number of phases (see Fig. 18).

τ = the pole-pitch.

(For G, g, and N_1 see under zigzag leakage.)

We find the slot constant from the following formulæ :—

$$S_1 = \frac{2\,c\,r_1}{3\,B_3} + \frac{r_9}{4\,B_3} + \frac{r_5}{B_3} + \frac{2\,r_6}{B_1 + B_3} + \frac{r_4}{B_1} \text{ (Fig. 21)} \quad . \quad . \quad (58)$$

$$S_1 = \frac{2\,c\,r_1}{3\,B_1} + \frac{r_9}{4\,B_1} + \frac{r_5 - d_s}{B_1} \text{ (Fig. 22)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (59)$$

or approximately from—

$$S_1 = \frac{c\,r_2}{3\,B_3} + \frac{r_5}{B_3} + \frac{2\,r_6}{B_1 + B_3} + \frac{r_4}{B_1} \text{ (Fig. 21)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (60)$$

$$S_1 = \frac{c\,r_2}{3\,B_1} + \frac{r_5 - d_s}{B_1} \text{ (Fig. 22)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (61)$$

These formulæ are different from the customary expressions in two respects :—

1. The value d_s has been introduced in case of the open slots. It will be remembered that in figuring the zigzag leakage the dispersion has been taken into account ; that means, that the lines L leaving the tooth sides have been taken into consideration in connection with the zigzag leakage. We must therefore subtract a certain amount from the slot sides when figuring the slot constant. Approximate values for this amount to be subtracted may be taken from—

$$d_s = .3\,B_1 - .6\,g.$$

In case of partially closed slots this subtraction does not need to be made, since the dispersion of the lines as shown at M in Fig. 21 will cause an increase of slot flux, which approximately counterbalances the above decrease.

2 The coefficient c has been added in the formula for S. It is intended to take approximately into account the effect of the eddy currents, which are induced by the slot leakage fluxes in the conductors, and which counteract the slot leakage fluxes. It will not be attempted here to give correct values for c. Probably c is slightly smaller than 1 for small wire ; between 0·95 and 0·90 for heavy wire, and between 0·75 and 0·90 for straps and bars, depending upon their thickness and depth.

The formula for the slot leakage may again be simplified by combining the coefficients k_t, k_p, and k into one—

$$K_s = \frac{k_t\,k_p}{k} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (62)$$

The values for K_s are given in Fig. 23.

We have now the primary slot leakage coefficient—

$$\sigma_{1s} = \frac{K_s g G S_1}{N_1 \tau} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (63)$$

For approximate calculations we may again assume K_s to be constant, and write—

$$\sigma_{1s} = \frac{10 \cdot 5 \, g G S_1}{N_1 \tau} \text{ for 3-phase} \quad . \quad . \quad . \quad . \quad . \quad . \quad (64)$$

$$\sigma_{1s} = \frac{11 \cdot 5 \, g G S_1}{N_1 \tau} \text{ for 2-phase} \quad . \quad . \quad . \quad . \quad . \quad . \quad (65)$$

It is a matter of course that simplified values for S may be introduced for any particular type of slots.

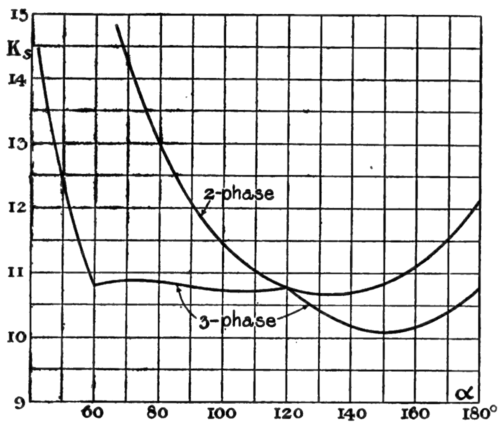

FIG. 23.

For fractional pitch windings with one coil per slot the slot leakage may be found, as in case of the zigzag leakage, by calculating the same for a full-pitch winding as outlined above, and multiplying the value thus found by—

$$\frac{1}{\sin^2 \frac{\alpha}{2}}.$$

5. SECONDARY SLOT LEAKAGE.

The formula for the secondary slot leakage is theoretically somewhat different from the primary, and in squirrel-cage rotors partly dependent upon the secondary resistance. The formulæ given for the primary slot leakage are, however, in practice close enough for the secondary slot leakage coefficient σ_{2s} also, if N_2 is introduced for N_1 and the secondary slot constant instead of the primary.

6. Belt or Differential Leakage.

This part of the leakage has been treated by the author in an article,* and two curves for its practical calculation are reproduced from there in Figs. 24 and 25. We may distinguish between a primary and secondary differential leakage coefficient. The primary coefficient σ_{1d} for a full-pitch winding may be taken directly from Fig. 24, corre-

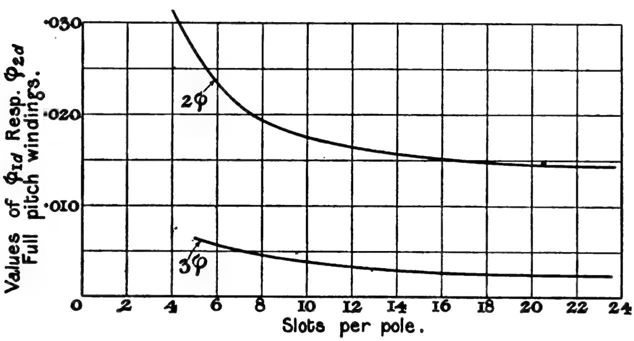

Fig. 24.

sponding to the number of slots per pole in the primary. For fractional pitch windings this value has to be multiplied with the value found from Fig. 25, corresponding to the primary pitch of winding. In case of a wound secondary the secondary coefficient σ_{2d} is to be found in a

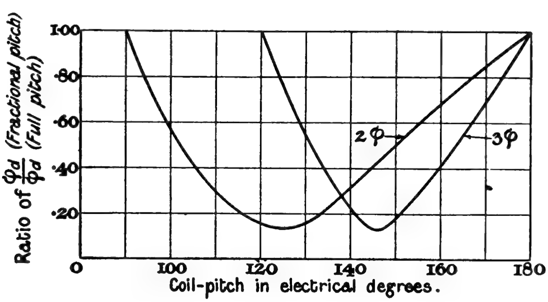

Fig. 25.

similar way, by reading the values corresponding to the secondary number of slots, number of phases, and coil-pitch. In case of a squirrel-cage secondary the secondary differential leakage coefficient may be set at zero.

* *Elektrotechnische Zeitschrift*, vol. 30, p. 841, 1909.

7. End Connection Leakage.

The end connection leakage problem is so complex that its exact mathematical determination is almost impossible. The writer has found it practicable, however, to find the primary coefficient form—

$$\sigma_{1e} = \frac{C g G L}{l \tau \sin^2 \frac{\alpha}{2}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (66)$$

L is the length of the end connections, l is the effective width of the air-gap or approximately the width of the iron core, C is a factor depending upon the style of winding employed.

The secondary end connection coefficient σ_{2e} is formed from the same formula by introducing C, L, and α, corresponding to the secondary winding. In case of squirrel-cage secondaries L is to be made equal to the pole-pitch τ, plus twice the length of the bar ends extending outside of the core, and the angle $\alpha = 180°$, therefore $\sin^2 \frac{\alpha}{2} = 1$.

The factor C varies largely with the style of winding employed, and is influenced by a large number of details of design, as has been pointed out in detail by the author in a previous article.* It should therefore be determined by test for each style of winding. This is easily possible from any standard factory test, made for determining the total leakage coefficient, if the primary type of winding is similar to the secondary winding. In this case C may be assumed to be equal for both members, and it is therefore the only unknown quantity in the equation for the total leakage coefficient. After C is known for a certain style of winding, this type of winding may be tested in combination with another type of winding in the other member—for instance, a squirrel-cage winding and C may be determined for the other type of winding.

For the form-wound coils, which are usually employed in connection with open-slot motors, C has been found as given in the following table :—

No. of Poles.	C.
2	0·45
4	0·55
6	0·60
8	0·70
10	0·75
12	0·78
14	0·80
16	0·83
18	0·85

* *Electrical World*, vol. 51, p. 179, 1908.

For the concentric winding usually employed in Europe C has been found to be 40 to 100 per cent. higher, but no reliable data are at hand. For squirrel-cage windings C has been observed to be between 0·4 and 0·5.

8. Total Leakage.

The total leakage coefficient may now be found from—

$$\sigma = (\sigma_z + \sigma_{1s} + \sigma_{2s} + \sigma_{1d} + \sigma_{2d} + \sigma_{1c} + \sigma_{2c}) \frac{A\,T_t}{A\,T_a} \quad . \quad . \quad . \quad (67)$$

$A\,T_t$ = total ampere-turns.
$A\,T_a$ = ampere-turns required for the air-gap.

The above is only correct under the assumption that the reluctance for the leakage fluxes in the iron is practically zero. This assumption is always justified for currents corresponding to the normal running currents of the motor. The writer has explained in an article * on the "Practical Testing of Induction Motors," that it is justified to make the short-circuit test with currents of about that size, and if this is done the above formula will give results which check very closely with the results found from test.

* *Electrical Review*, N.Y., vol. 50, p. 108, 1907.

ORIGINAL COMMUNICATION.

THE ARRANGEMENT OF EXPERIMENTAL ELECTRICAL CIRCUITS FOR LABORATORIES.

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The question of the equipment of laboratories for experimental work as regards the distribution of electric current first came to my notice some ten years ago when Professor Arthur Schuster commissioned me to prepare a scheme for the new Physical Laboratories about to be built for the Manchester University. At that time there was no physical laboratory in this country in which any elaborate system of distribution had been adopted. It was therefore considered advisable to see what was being done on the Continent, and for that purpose the then recently completed Electrotechnical Institute in Darmstadt was selected for a visit of inspection. From the observations made at this Institution, together with valuable advice and suggestions from Professor Schuster, a scheme of electric distribution was evolved for the Manchester Laboratories, and the installations that have been erected in recent years, and of which I propose to give short descriptions later, are the outcome of the experience gained at Manchester.

In arranging a distribution scheme for laboratory work we have to consider the special requirement of a laboratory, in which the chief objects to be attained are :—

1. To supply a source of current that will give a steady pressure.
2. To provide a centre of distribution such that various voltages can be made available on different circuits simultaneously.
3. To arrange a network of circuits that shall be as inexpensive as possible in first cost, that will lend itself easily to alterations or additions, and that will maintain a high insulation resistance.

Source of Current.—For laboratory purposes a battery of accumulators is essential as furnishing the only means of providing absolutely steady currents. It may be said that any standard make of secondary battery will suffice, provided that the plate selected will allow of a high rate of discharge if required. The question then arises as to the best arrangement for charging the cells. Leaving out of account the cases where the laboratory has its own generating plant, we will consider the question of a supply from public mains. In the majority of cases we may take the voltage available to be between the limits of 200 and 250. As a general rule, the battery will consist of from 30 to 55 cells, which means that the maximum voltage required will be 140. There are then two alternatives, either to charge direct from the mains through a suitable rheostat or to instal a motor-generator. As you cannot expect to obtain a greater combined efficiency than 70 per cent. from a motor-generator of comparatively small size, it will be noted that the losses will be the same in both cases if the supply is 200 volts, and will be in favour of the motor-generator set when the supply voltage exceeds that amount. As an alternative to an ordinary motor-generator we have now available a direct-current motor converter. I am informed by the makers that for a machine of 12-k.w. output converting direct current from 200 to 140 volts, an efficiency of nearly 90 per cent. can be guaranteed. We have, however, more important considerations to take into account than percentage efficiency. We have to take into account that the cells will be unevenly discharged as explained later, and that we have therefore to provide means for obtaining low voltages down to, say, 15 or 20 volts. It would then appear to be most convenient to split the generator into two and instal either a dynamo at, say, 110 volts and a small booster at 50 volts (assuming that 140 is the charging voltage for the whole battery), or two similar dynamos giving 70 volts each. In the former case the two machines would be used separately or in series and would each be driven by a motor; or, again, two converters of the type referred to above would be installed. In the latter case the two machines can be mounted on one bed-plate with the motor in the centre, all three machines driving on one shaft. The generators can be used separately, in series, or in parallel. The second arrangement is on the whole the more convenient of the two, because we get the additional advantage of having a set eminently suitable for running lecture table arc lamps and also providing a heavy current by paralleling the two machines. Of course, a machine giving 110 volts is almost as useful as one giving 70 volts for arc lamp work. The choice will then depend on the requirements, and, generally speaking, the first alternative is the more convenient for a physical laboratory and the second for a chemical laboratory where heavier currents are as a rule required. Next comes the provision for alternating current. Here, again, two cases arise. First, where the supply is continuous current, it will be found convenient to instal a motor-generator and possibly to arrange the dynamo with slip-rings, so as to make provision for 1-, 2-, or

3-phase current. Secondly, where the supply is alternating, it will be merely a question of providing a suitable transformer for the requirements of the laboratory. In physical laboratories a single-phase alternating current is all that is required in the majority of cases, and the demand for current is not likely to exceed 25 amperes. But the chemical laboratory will require much heavier currents for furnace work. I believe that for certain types of furnace an alternating current is found to be most suitable and the current required may be anything up to 2,000 amperes. The heaviest currents will be used at comparatively low voltages ranging from 26 to 50 volts. The question arises as to the best type of generator to instal for furnace work. I am inclined to follow the practice in America and have a single-phase machine with the armature divided into four exactly similar sections, so wound that the four sections can be coupled up in series or in parallel. In the machine that I have selected each section has an output of 350 amperes at 25 volts, so that we get from the machine either 1,400 amperes at 25 volts, 700 amperes at 50 volts, or 350 amperes at 100 volts. The voltages may be further varied within certain limits by varying the excitation of the fields. In cases where an alternating current is available a transformer can be used on similar lines. In the Massachusetts Institute of Technology a 50-k.w. transformer is provided. The primary is connected to a 1,100-volt circuit. There are 16 independent secondaries, so wound that each can deliver 300 amperes at 10 volts. The terminals are arranged so that the sections can be placed in series or in parallel. At the Columbia University Laboratory a set such as I have just described is used. There they have a 50-k.w. alternator driven by a direct-current motor. The armature is divided into four sections, arranged so as to be connected up in series or in parallel giving voltages of 25, 50, or 100, with the full current of 2,000 amperes available at the lowest voltage.

Distribution.—Here the most important requirement is to arrange a method of delivering current at any desired voltage to any of the laboratory circuits, and to ensure that the arrangement can be easily manipulated without loss of time from a convenient centre. The voltages may vary from, say, 4 up to 110, but except for certain electrolytic experiments it is probably most convenient to arrange the source of current so as to vary the voltage in multiples of ten. This being the case, we divide the battery into groups of five cells and arrange our distribution board so that these groups of cells can be connected up in series to give the necessary voltage. We then have to design the distribution board so that the groups of cells can be discharged on to any of the circuits as required. The actual type of board that I am in the habit of using for this purpose I propose to describe later, but I may perhaps here say that it is convenient to combine with the actual panels for distribution a special charging panel and also a panel to afford a simple means of connecting the groups of cells in parallel for obtaining large currents in those cases where such an arrange-

ment is necessary, which will be more particularly the case in chemical laboratories.

Circuits.—Now as regards the circuits themselves, what type of conductor is the most suitable to employ? The choice lies between insulated conductors and bare conductors, and I propose to show that the use of the latter is far more satisfactory from every point of view. The advantages chiefly lie in the cost of material and erection, and in the facilities afforded for making alterations and additions, such as tapping off extra terminal positions. Suppose we consider the necessary conductor required to carry 25 amperes. If we use an insulated conductor we should naturally work to the rules of this Institution, and the size of conductor for this current would be $\frac{7}{16}$. Now in the case of a bare conductor we can work at a much higher current density, and we have merely to consider what limits of heating in the conductor we can allow and the corresponding drop in pressure at the end of the line. Some years ago, in order to arrive at a satisfactory current density to be used for bare conductors, so as to allow of reduction of weight to a minimum and still not to risk any undue heating, a series of experiments were made and the following formula was finally decided upon to be used for laboratory circuits :—

$$C^2 = 15\ D^3,$$

where C is the current in amperes and D the diameter in millimetres.

This formula gives us 22·7 amperes for a No. 10 S.W.G. wire. The drop in voltage per 100 ft. double run is therefore, in this case, nearly 2·9 volts. It may be of interest to add that a No. 10 bare copper wire will rise 18° F. from 75° F. in a room when carrying 26 amperes. Whereas to produce the same rise in the open air on a calm day in summer 42 amperes are required.*

Now we see from the above that we have to compare a bare No. 10 copper wire with a $\frac{7}{16}$ cable as regards cost, the price of the former, taking copper at 9d. per lb., being about 12s. per 110 yards, and of the latter about £5 per 110 yards. Again, in erection it is not at all objectionable to run bare conductors overhead, spanning from point to point to obtain the shortest runs. It will, I think, be admitted that this is hardly feasible with insulated cables of $\frac{7}{16}$ and above. So that in addition to the saving on the conductor, we shall most probably use a smaller length of bare conductor for any particular circuit. The great point in using bare conductor is to have a really first-class insulator, and if the conductors are carefully erected, one can rely on obtaining a very high insulation resistance in a dry building. As an illustration, in a laboratory that has been recently equipped an insulation resistance of over 100 megohms has been obtained on each individual circuit, which is satisfactory taking into account that the conductor will on the average be carried on at least a dozen insulators and possibly pass through several walls.

* See *Modern Electric Practice*, vol. 3, p. 79.

Reverting for a moment to the voltage drop in connection with those circuits where a low voltage is likely to be used, in most cases where low voltages are required, and by low voltage I mean up to 10 volts, the current used for an experiment is not likely to exceed 5 or 6 amperes. Supposing, however, we take a demand of 10 amperes, at 10 volts we get with our No. 10 copper conductor on a circuit of 100 ft. run (and very few runs are likely to exceed this length) a total drop on lead and return of 1·27 volts, and at 6 amperes the drop would only be 0·76 volt.

We will now consider the arrangements for distribution.

Distribution.—Take first the simplest case where we desire to attribute currents from a battery of, say, 30 cells, giving steps of 10 volts. We divide the battery into groups of cells, in this case six groups of five cells each. Therefore, by placing one or more groups in series, we get

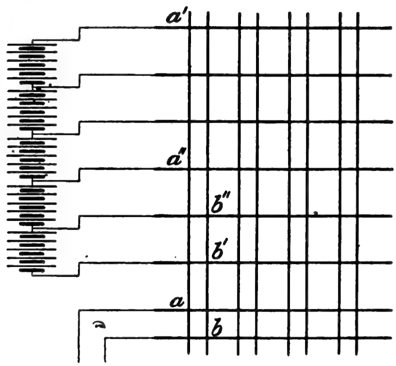


FIG. 1.

10, 20, 30, 40, 50, and 60 volts available. Now, if we have a panel with seven busbars connected, as shown in Fig. 1, to the cells, by connecting the ends of any circuit to two of these busbars we place on that circuit the voltage corresponding to the position of those bars.

Instead of using switches the most convenient arrangement is to have a series of horizontal and vertical bars drilled at each intersection and fitted with plugs to make contact between a horizontal and vertical bar. Fig. 1 shows diagrammatically such a board fed by five groups of cells and distributing to four circuits. Here we see an arrangement by which we can distribute current from the cells to any of four circuits at voltages varying from 10 to 50 in 10-volt steps.

It is, however, convenient to be able to charge the cells without having to disconnect the plugboard. For this purpose we then add two more horizontal bars, which bars are connected to the dynamo through the usual apparatus such as automatic cut-out, ammeter, etc.

Referring to the figure, it will be seen that by inserting plugs at *a*, *a'*, and *b*, *b'*, we can charge the whole battery or we can pick out a single group to charge by inserting plugs at *a*, *a''*, and *b*, *b''*. It will be noticed that with this arrangement we can also place current direct from the dynamo on to any of the circuits.

The next arrangement is to have means available for connecting up the group of cells in parallel for use on a special circuit. This is effected by the device shown in Fig. 2. Here we have a pair of leads brought from each group of cells to the plugboard instead of connecting all the groups together in series at the battery. We split the horizontal bars in two pieces and interpose a single-pole switch between the two portions. Referring to the figure, you will notice that so long as all the switches are closed we have all the groups in series as before, and for using the four circuits we proceed in the same

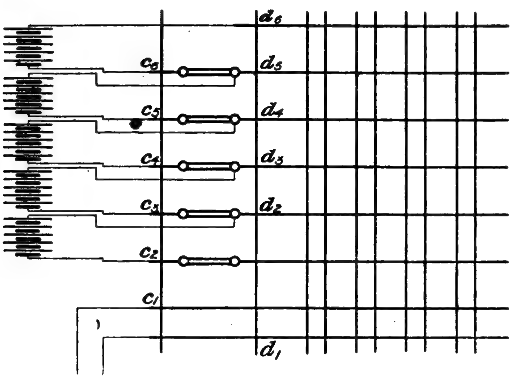


FIG. 2.

way as in Fig. 1. If, however, we wish to have the groups in parallel on to the special circuit we simply open all the switches and insert plugs at points marked C_1 to C_6 and D_1 to D_6. As far as connections for charging are concerned we use these same plug positions. Thus to charge the whole battery we keep all the switches closed and plug at C_1, C_2, D_1, D_6; or, supposing we desire to charge the third group from the top, we open the second and third switches and plug at C_1, C_4, D_1, D_4. Now, in a great many cases it is convenient to have two separate batteries, so that one battery is always available for discharge. In this case we have to devise an arrangement so that one battery can be charging whilst the other is discharging and *vice versâ*. This arrangement is effected as shown in Fig. 3. Here on the charging panel we have two identical sets of bars and plugs on each side of a vertical row of double-pole change-over switches. The centre short bars are so arranged that when all their plugs are inserted we have

the corresponding cells all in series. The object of these short centre-bars is to enable a single group or number of groups to be selected for individual charging. By means of the change-over switches in the centre it is possible to connect either battery to the distributing panel, and the complete arrangement enables the one battery or any part thereof to be charged simultaneously with the discharge of the other or any part of it. Referring to the figure, supposing we desire to charge the whole battery on the left and take a discharge from the battery on the right, we place all the change-over switches to the right, which entirely disconnects the left battery from the distributing panel and at the same time places the right battery in connection with

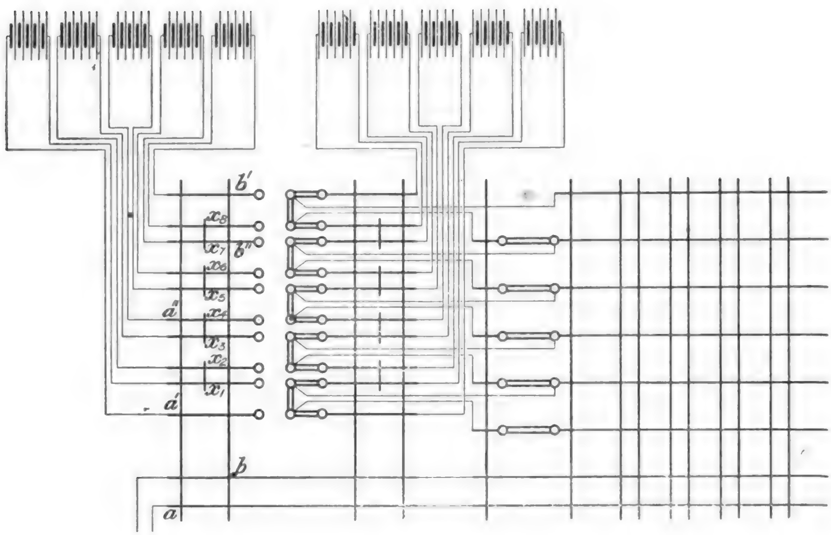


FIG. 3.

that panel. We then insert plugs at *a*, *a′* and *b*, *b′*. Or supposing it is necessary to charge the second and third groups from the top, we take out plugs at X_4, X_7 and plug at *a*, *a″* and *b*, *b″*. Conversely, if the battery on the right is to be charged and that on the left discharged, the change-over switches are placed to the left and the corresponding plug contacts made as before. Either set of groups of cells can be placed in parallel as described previously.

Summarising the above: A board, as indicated in Fig. 1, gives a method of placing different voltages from a number of groups of cells or direct dynamo current on to a number of circuits and affords means of charging the whole battery or any part thereof.

A board, as indicated in Fig. 2, gives method of placing different

voltages from a number of groups of cells or direct dynamo current on to a number of circuits or of placing the groups of cells in parallel on to a special circuit, together with arrangements for charging the whole or any part of the battery.

A board, as indicated in Fig. 3, gives a method of placing different voltages from a number of groups of cells in either of two batteries on to a number of circuits or of placing the groups from either battery in parallel on to a special circuit, also of charging either battery or any part thereof and of placing direct dynamo current on to any circuit. And it is further to be noted that one battery can be charging simultaneously with the discharge of the other.

In a large laboratory it may not always be convenient to run every circuit back to the main distribution board, but this difficulty is easily overcome by using additional plugboards to subdivide the circuits further. This branch board will be merely a repetition of that shown in Fig. 1.

Now, as regards the connection of circuits to the plugboards, I have adopted two different methods. In the first, two series of busbars are used arranged at right angles to one another on either side of an insulating slab. What may be called the feeding busbars are placed horizontally at the back, and the distributing busbars are placed vertically on the front. A hole is drilled through both bars and the slab at each intersection, and a plug can then be inserted where desired to connect the front and back bars together. The circuit wires are connected through fuses to the ends of the vertical busbars. These plugs have presented some little difficulty. It is of great importance that the contact should be electrically and mechanically sound, and that the contact between back and front bars should be made expeditiously. The first two objects can be attained with a plug having a screw connection at one end and a cone at the other, but this is expensive. It means, first, an expensive plug, and it necessitates tapping the holes in the back bars and providing the front bars with coned seatings. You may be able to rely upon the screwed contact, but the cone and its seating are liable to wear and finally to become unsatisfactory. The next type of plug, consisting simply of a brass sleeve split at each end, does away with the objection of having tapped holes and coned seatings, thereby saving expense. The plug itself is also reasonable in cost and is, further, quick in manipulation, but though fairly reliable as regards contact it is not entirely so. Both these types of plug are in use, but the final type of plug, which I now use exclusively, is most reliable and inexpensive. This type is shown in Fig. 4. You will notice that it consists of a brass sleeve internally tapered towards each end. Through the centre runs a spindle on which work two coned pieces of brass on a right- and left-handed thread. The spindle is rigidly connected to the handle, which, when rotated, causes the two cones to move inwards, thereby pressing the ends of the sleeve, which are split to allow of expansion outwards. The rotation of the handle after the plug has been placed in position in the holes causes the plug to

expand inside the holes. With this plug only parallel holes are required, and the contact obtained is electrically and mechanically perfect.

We now come to the second method of connecting the circuits to the boards. The advantages of the second method about to be described lie chiefly in a saving of cost in manufacture of the boards. In this method the vertical busbars are entirely dispensed with, and the horizontal bars are placed on the front of the slab. The circuits themselves are brought down to a fuse panel, Figs. 5 and 6, and flexible cords are brought from the underside of the fuses over a system of pulleys and counterweights to appropriate positions on the front of the slab, so that the plug connected to the flexible can be connected to the busbars as required. The plug in this case has only to make a single contact and

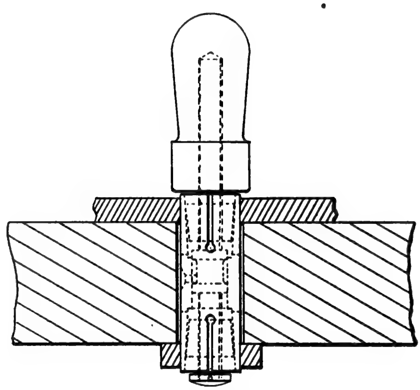


FIG. 4.

is constructed on the same principle as the double contact plug, but with a single internal cone working on the spindle. The saving in cost of this type of board is effected through the saving of the circuit busbars, and the saving in drilling of the slab, the latter being a considerable item. The saving here indicated more than compensates for the cost of the pulleys and counterweight gear. The chief difficulty with this design arose in connection with the flexibles. Great difficulty was experienced in obtaining a flexible conductor to carry up to 50 amperes sufficiently flexible to run nicely over a 3 in. pulley. Several makers in this country were tried without success, but a flexible conductor was finally obtained in Germany consisting of 3,081 strands of No. 48 S.W.G. The conductor is not insulated but merely covered with a braiding of soft cotton, as it was decided to trust to the pulleys for insulation. This decision has been justified as on the circuits, as mentioned earlier in this paper, an insulation resistance of over 100 megohms has been obtained including the flexibles themselves,

which will be roughly $2\frac{1}{2}$ yards long from fuse to plug. The pulleys are made of lignum vitæ, with brass bushes working on a steel shaft.

I propose now to describe one or two arrangements which have been adopted for special purposes in connection with distribution of current. In the first place, it may be of interest to describe a device designed to prevent plugs being inserted into wrong holes on distributing panels.

Supposing we take the case of a distributing panel for eight circuits, that means we have 16 busbars, and in this particular case we arrange that the vertical circuit bars shall be at the back and the horizontal feeding busbars on the front. We desire to ensure that one plug only can be inserted in any horizontal bar at the same time. For this purpose we have an ebonite guard bar fitted between the busbar and the slab and

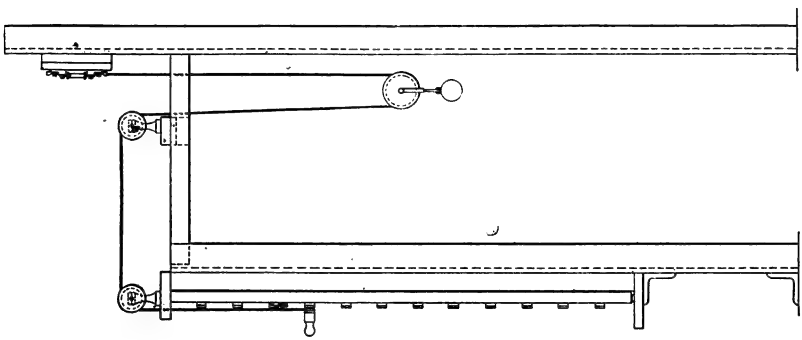


FIG.

free to slide backwards and forwards parallel to its length. There are the same number of holes in the ebonite bar as there are in the horizontal brass bar, but the holes are so spaced that when one hole in the ebonite bar corresponds with a hole in the brass bar, and so allows a plug to go through both, all the other holes are out of adjustment. The spacing of the holes is found as follows: Suppose we space the holes in the brass bar at $1\frac{7}{8}$ in. centres. We have 16 holes, so that the total distance between the two extreme holes is $15 \times 1\frac{7}{8}$ in.; if we take $\frac{16}{15}$ of this length and divide the result by 15 we get as the result 2 in., which will be the spacing for the holes in the ebonite bar. And it will be found that this spacing satisfies the condition required.

The second special application of plugs that I propose to describe is an arrangement for high-tension work to prevent accidental contact with busbars carrying a high-tension current. We have a plugboard arranged to place four sections of a transformer secondary in series or in parallel. Assume the transformer primary to be fed by a single-phase alternating current at 100 volts, and that the secondary

is split into four equal sections, each giving 250 volts. These four sections are connected to a board arranged as indicated on the wiring diagram, Fig. 10, in the top right-hand corner, by eight conductors, and by means of double contact plugs these four sections are connected up

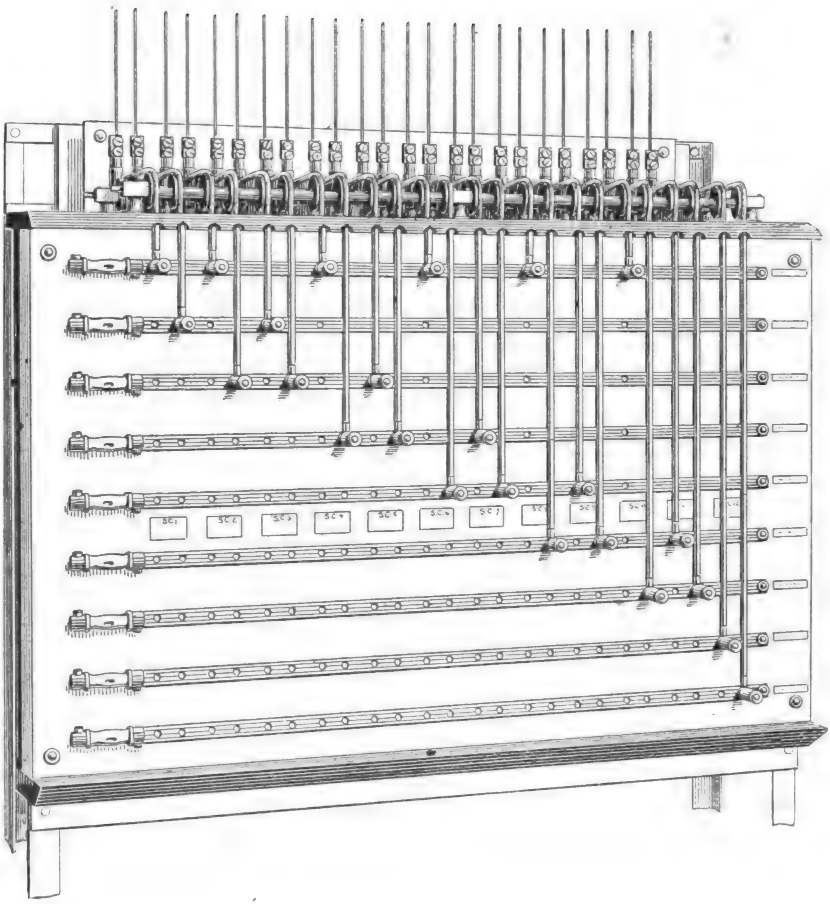


Fig. 6.

in series to give 1,000 volts to the external circuit, in parallel to give 250 volts, or in multiple series to give 500 volts. Such an arrangement might be a source of danger to students, so a guard device is necessary to prevent accidental contact with the busbars. In the first place, a sheet of plate glass, perforated with the necessary holes to allow of the insertion of plugs in the proper positions to obtain the required

voltage, is fitted on the front of the board. The double contact plugs are fitted with elongated handles in which are cut circular grooves. An ebonite bar, pivoted at both ends and therefore free to move about an axis parallel to its length, is provided at proper intervals with slots, which engage with the grooves in the plug handles. One end of the ebonite bar is connected by means of a link with the handle of a

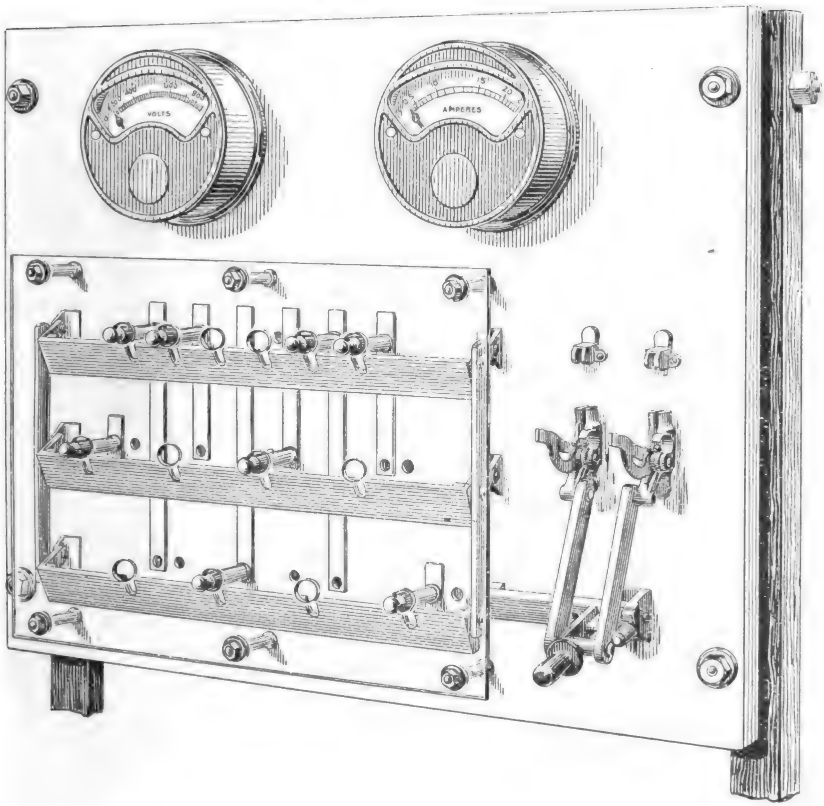


FIG. 7.

double pole switch, which is placed into the primary circuit of the transformer, and is so set that when the switch is closed all the plugs are locked by the ebonite bar and can only be moved after opening the switch. Thus when the busbars are alive the plugs can neither be inserted or withdrawn. Fig. 7 is a photograph of this type of board.

Generally speaking it is obvious that a combination of plugs and

switches can be arranged to meet almost any desired purpose, and I should like to point out the very great convenience arising from these arrangements in laboratory work. There is a great saving of time and trouble in being able to set your connections in a simple way by means of these plugboards, instead of having to work with loose wires and cables.

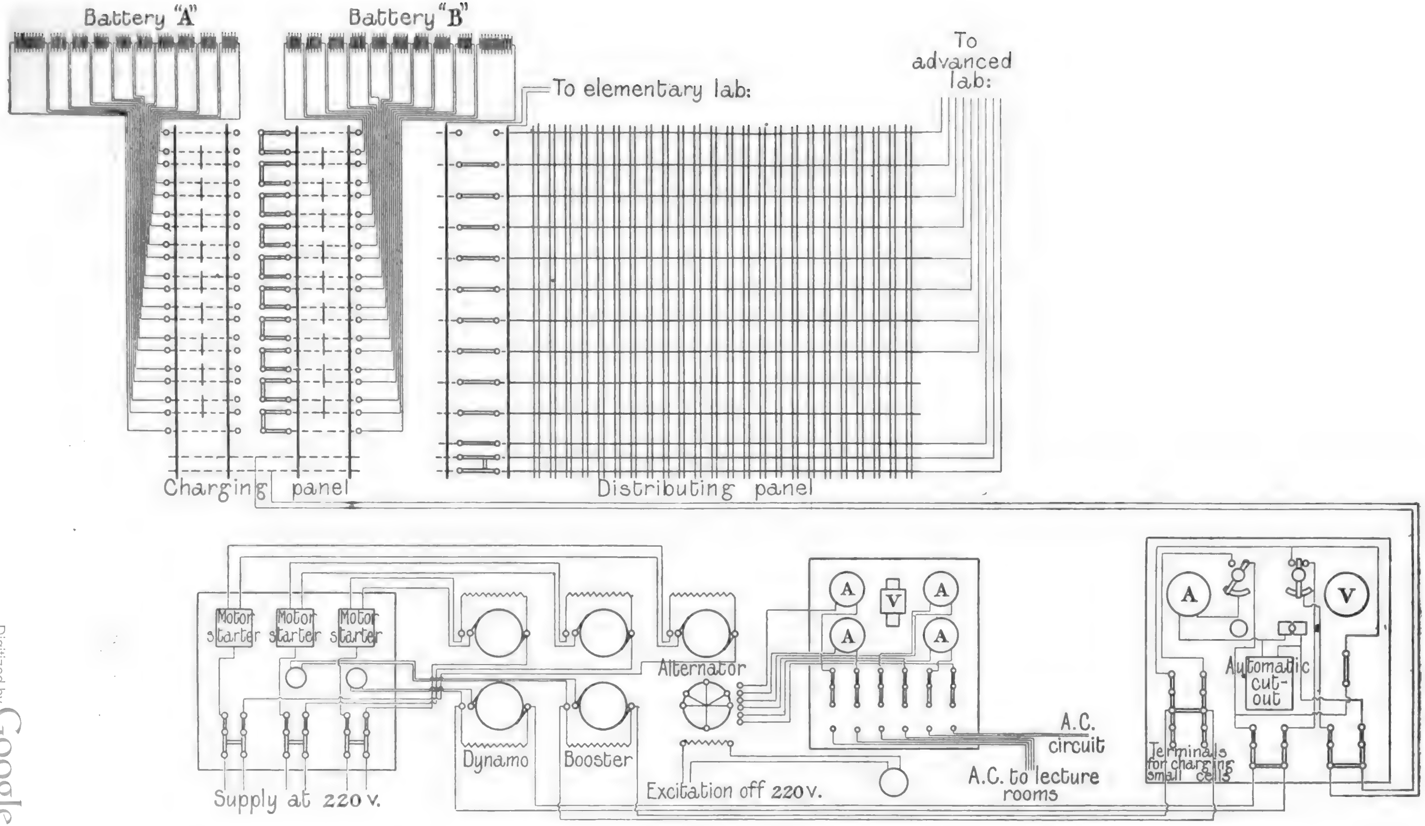
Terminals for connecting Apparatus to the Circuits.—In designing the general scheme for a laboratory we have to consider the requirements of three classes of students:—

1. Elementary.
2. Advanced.
3. Research.

1. The requirements for elementary students are for most purposes met by small portable batteries. But it is convenient to have circuits available for use from the central distribution system as well. It is not necessary to provide the elementary laboratory with a large number of independent circuits, as the experiments conducted by these students can be performed very well off a single circuit or possibly a pair of circuits. The current required by each student will be small and the voltage low. The most convenient arrangement is probably to feed the elementary laboratory with a couple of 50-ampere circuits, and arrange a series of tappings off the circuits, whose number will depend on the number of students working together in one class.
2. In the case of more advanced students it is best to set apart a number of circuits for their exclusive use, feed these on to a separate plugboard, and wire the necessary number of terminal positions off this plugboard, arranging so that not more than two students are working off the same circuit simultaneously.
3. For research work it is advisable that each terminal position should be an entirely independent circuit, so as to ensure absolutely steady currents and avoid any risk of the circuit being interfered with by another experiment.

Capacity of Circuits.—The capacity of the various circuits must depend upon circumstances in each particular case, but generally speaking, physical laboratory circuits are best arranged for 20 and 50 amperes, and those in chemical laboratories for 50 and 100 amperes.

Special Conductors.—In certain rooms of a physical laboratory it is necessary to eliminate all possible magnetic effects from the circuits. This can be attained either by crossing the conductors at short intervals, or by changing from bare conductors to insulated concentric cables.



Battery "A"
Battery "B"
To elementary lab:
To advanced lab:
Charging panel
Distributing panel
Motor starter
Motor starter
Motor starter
Dynamo
Booster
Alternator
A
V
A
A
A
A.C. circuit
A.C. to lecture rooms
Excitation off 220 v.
Supply at 220 v.
A
V
Automatic cut-out
Terminals for charging small cells

FIG. 8.

For furnace and other heavy current circuits copper strip may be conveniently used, fitted on iron brackets with the usual pattern of busbar insulator. A current density of 2,000 amperes per square inch may be used, as a drop in pressure is not material, and these circuits are usually very short. For the lecture tables it is best to bring the bare copper as close to the table as may be convenient, and then finally connect up to the terminals on the tables with insulated conductor.

The following paragraphs contain short descriptions of recent laboratory equipments in which the foregoing principles have been embodied:—

Case A.—Physical Laboratory.

Supply: 220 volts direct current, 3-wire system, 440 on outers.
Source of current:—

Dynamo driven by 220-volt motor, 80 amperes, 110 volts.
Dynamo driven by 220-volt motor, 80 amperes, 30 volts.
Alternator driven by 220-volt motor fitted with six slip-rings, for 1-, 2-, or 3-phase current:—

Single-phase, 17 amperes, 140 volts.
Two-phase, 11 amperes, 140 volts.
Three-phase, 14 amperes, 120 volts.

Two batteries of 55 cells, 200 ampere-hour capacity.

The dynamos and cells are connected to a main plugboard of the type shown in Fig. 3. The circuits to the plugboard are connected according to the method shown in Fig. 5. There are twenty-four circuits distributing current through the laboratories. In the advanced laboratory there is a sub-board off which twelve circuits are taken for the advanced students. One large circuit feeds the elementary laboratory with a series of tappings to feed the various benches. The conductors are of bare copper, except in the elementary laboratory, where the conductors are laid in trenches in the floor and are therefore insulated. The cables are insulated with vulcanised bitumen, as are also the cables which feed the terminals on the lecture tables.

Case B.—Chemical Laboratory.

Supply: 220 volts direct current, 3-wire system, 440 on outers.
Source of current:—

Two dynamos driven by a single motor off 440 volts, the three machines working on one shaft with the motor in the middle. Output of each dynamo, 50 amperes, 65 volts.
Single-phase alternator driven by 440-volt motor, having total output of 35 k.v.a. with armature in four sections to be connected in series or in parallel.
One battery of 48 cells, 220 ampere-hour capacity.

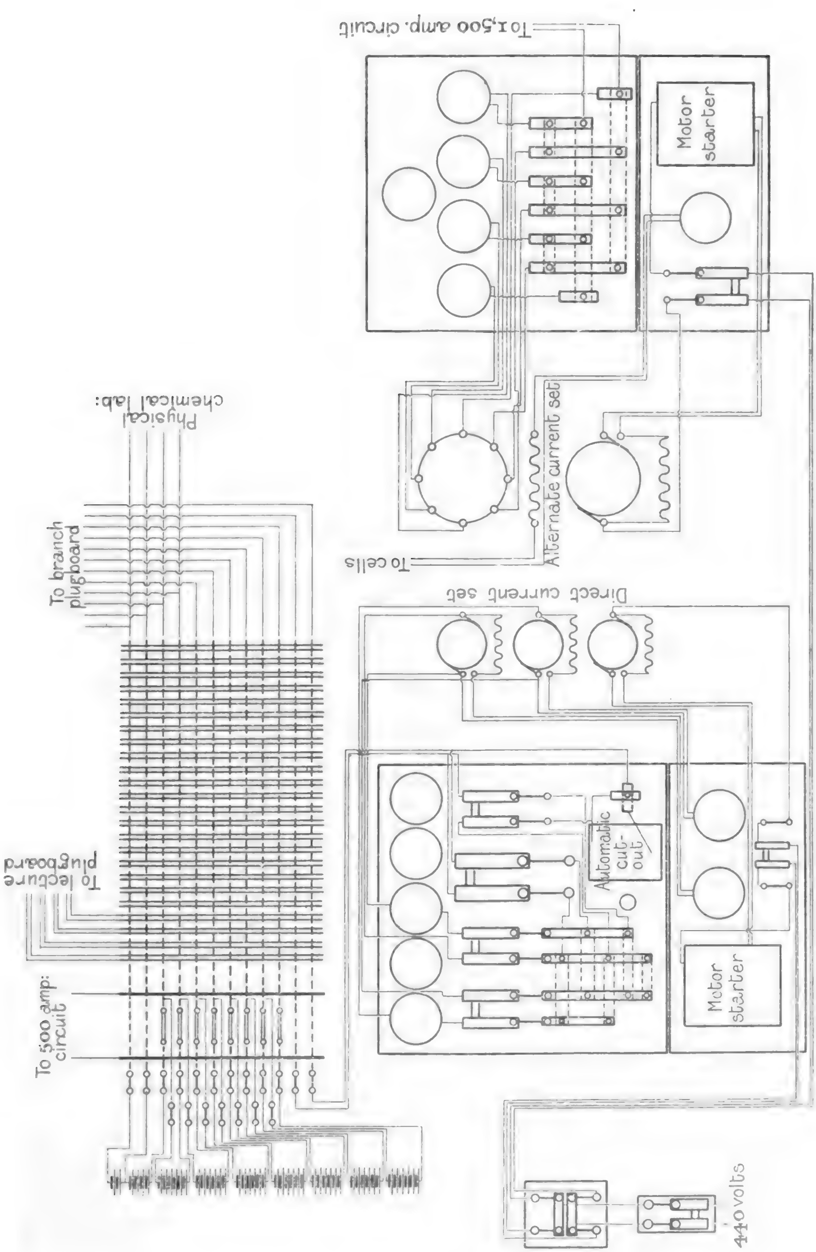

To 1,500 amp. circuit
Motor starter
Physical chemical lab:
Alternate current set
To cells
To branch plugboard
Direct current set
Automatic cut-out
To lecture plugboard
To 500 amp: circuit
Motor starter
440 volts

Fig. 9.

The battery is divided into nine groups of cells, seven groups of six cells each, one group of four cells, and one of two cells. These groups of cells are connected to a plugboard, shown in Fig. 2, and also to a sub-board of the type shown in Fig. 1. Off the main plugboard there are twenty-four circuits, four of which feed a second sub-board for the lecture-room circuits. In addition a special 4-wire circuit feeds the physico-chemical laboratory, the four wires being connected to the four top busbars of the main board. As these four busbars are connected to the first three groups of cells, consisting of two, four, and six cells respectively, we can obtain on this 4-wire circuit 4, 8, 12, 20, or 24 volts. The alternator is connected to a plugboard, which enables the four armature sections to be connected as required to the heavy current circuit. This circuit, which runs to those positions where furnace operations are to be performed, consists of copper strip of section 2 in. by $\frac{3}{8}$ in. All the conductors are of bare copper, with the exception of the conductors feeding the lecture tables, which conductors are insulated with vulcanised bitumen.

CASE C.—PHYSICAL AND ELECTRICAL LABORATORIES.

Supply: 200 volts direct current, 3-wire system, 400 on outers.
Source of current:—
Two dynamos driven by a single motor off 400 volts, the three machines working on one shaft with the motor in the middle. Output of each dynamo, 40 amperes, 65 volts.
Alternator fitted with six slip-rings driven by 400-volt motor.
Output: Single-phase, 60 amperes, 100 volts.
Two-phase, 30 amperes, 100 volts.
Three-phase, 38 amperes, 90 volts.
One battery of 50 cells, 240 ampere-hour capacity.

There are two different buildings here, one for pure physics and one for electricity. All the plant is situated in the electric laboratory. The battery is divided into ten groups of five cells each, seven of these groups are for use in the physics laboratory, and the other three for use in the electric laboratory, but arrangements have been made so that the whole battery is available in either building. In the physics laboratory there is a distributing plugboard of type shown in Fig. 1, fed by seven groups of cells from the electric laboratory, but in addition to the current from the cells arrangements are made on the plugboard for distributing alternating current from the alternating-current machine and also current from the 200-volt supply mains. It is to be noted that this board is fitted with ebonite guard-bars described earlier in this paper. Off this board there are eight circuits for feeding the various rooms of the physics laboratory.

The electric laboratory has a small plugboard fed by three groups of cells, and also with arrangements for current from the 200-volt mains. Off this board there are three circuits for the rooms of the

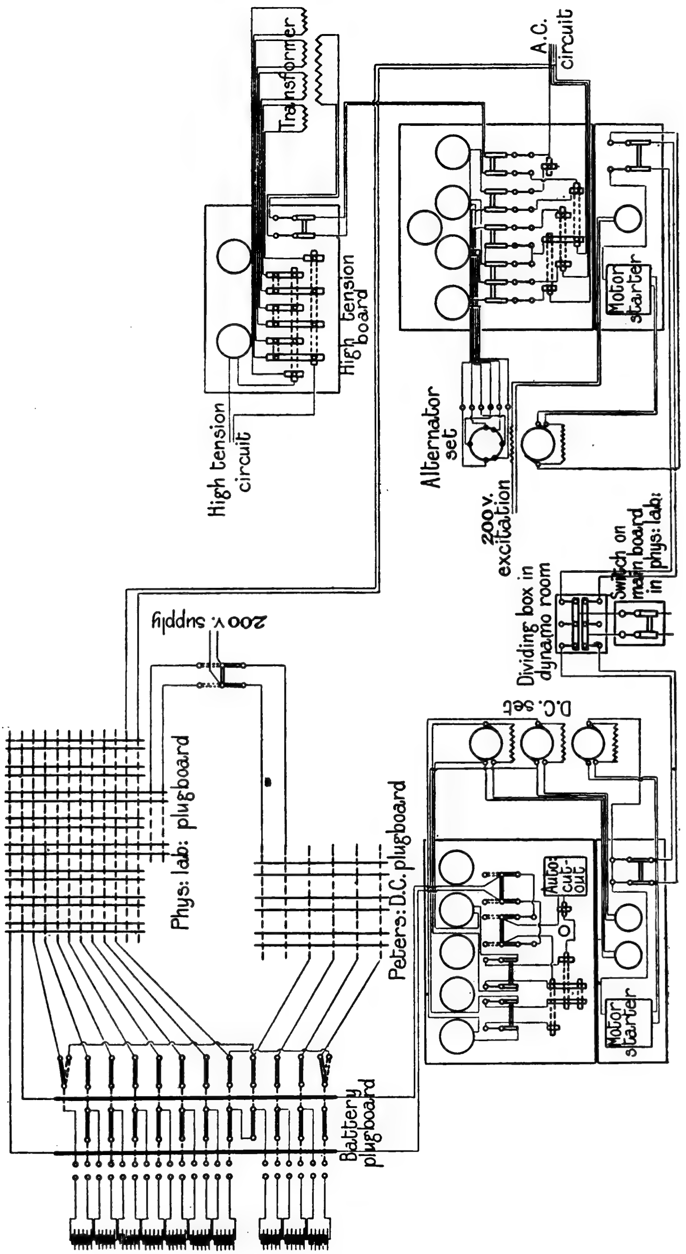
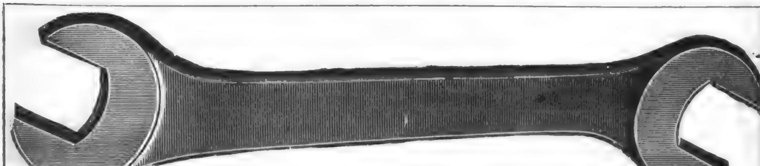
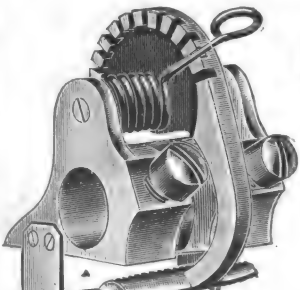

Transformer
High tension board
High tension circuit
A.C. circuit
Alternator set
200 v. excitation
Motor starter
Switch on main board in phys: lab:
Dividing box in dynamo room
200 v. supply
D.C. set
Phys: lab: plugboard
Peters: D.C. plugboard
Auto: cut-out
Motor starter
Battery plugboard

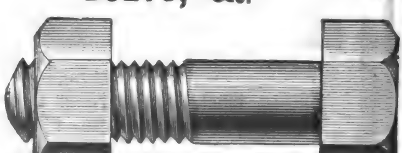
FIG. 10.

laboratory. The alternator is connected up to a switchboard, and off the switchboard there are two circuits, one a 2-wire circuit which runs to the high-tension room where it feeds a transformer, the other a 4-wire circuit which runs to the alternate-current room, and enables either 1-, 2-, or 3-phase currents to be used there. The transformer just mentioned in the high-tension room is a single-phase transformer fed at 100 volts on the primary, and with the secondary divided into four similar sections, each giving an output of 6 amperes at 250 volts. Eight leads are taken from the secondary to a board, as shown in Fig. 7, where they can be connected up as required.

Three general diagrams, Figs. 8, 9, and 10, indicate the connections adopted in the three cases just cited, from which diagrams a clear idea of the laboratory installations may be obtained.







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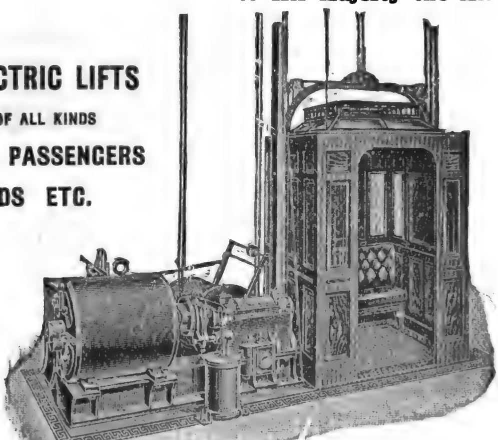

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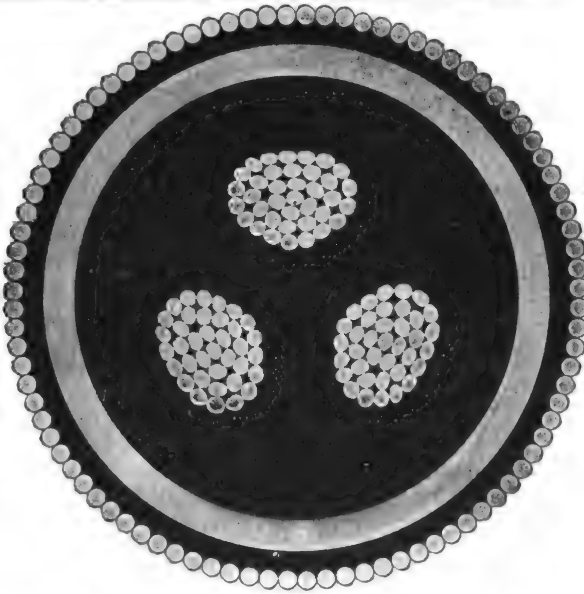

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JOURNAL

OF THE

Institution of Electrical Engineers.

Founded 1871. *Incorporated* 1883.

VOL. 45. 1910. NO. 203.

Proceedings of the Five Hundred and Fourth Ordinary General Meeting of the Institution of Electrical Engineers, held in the Rooms of the Institution of Civil Engineers, Great George Street, Westminster, on Thursday evening, March 10, 1910—Dr. GISBERT KAPP, President, in the chair.

The minutes of the Ordinary General Meeting, held on February 17, 1910, were taken as read, and confirmed.

Messrs. F. N. Haward and H. M. Sayers were appointed scrutineers of the ballot for the election of new members, and, at the end of the meeting, the following were declared to have been duly elected :—

ELECTIONS.

As Member.

Robert Manson Wilson.

As Associate Members.

Archibald Campbell Adams.
Harry Munro Campbell.
Peregrino Samuel Fernandez.
Reginald Henry Handcock.
Christopher George Roach.
Bernard Scheuer.
Francis Edward Spencer.
Edward Turner.
George Victor Twiss.
Ernest August Ullmann.
Arthur Vincent Vowles.
Horace George Weaver.

As Associate.

Jotsing Harising Advani, B.Sc.

Donations to the *Library* were announced as having been received since the last meeting from Dr. L. A. Bauer, The Engineering Standards Committee, A. Hands, H. R. Kempe, F. E. Nipher, Major W. A. J. O'Meara, C.M.G., The Phœnix Assurance Company, Ltd., P. O. Pedersen, The Secretary of the War Office; to the *Building Fund* from Professor J. Epstein, J. H. Garrett, Professor A. Hay, R. Hardy, E. Mercer, E. H. Rayner, G. M. Robertson, J. C. Smail, L. C. B. Trimnell; and to the *Benevolent Fund*, from Major P. Cardew, Sir J. Gavey, C.B., J. Gilligan, Colonel H. S. Hassard, J. R. P. Lunn, Major W. A. J. O'Meara, C.M.G., F. C. Raphael, J. B. Smith, and C. P. Sparks, to whom the thanks of the meeting were duly accorded.

The following papers, by Mr. Miles Walker, were read and discussed (see pp. 295 and 319):—

"Short-circuiting of Large Electric Generators and the Resulting Forces on Armature Windings."

"The Design of Turbo Field Magnets for Alternate-current Generators with Special Reference to Large Units at High Speeds."

The meeting adjourned at 9.35 p.m.

SHORT-CIRCUITING OF LARGE ELECTRIC GENERATORS AND THE RESULTING FORCES ON ARMATURE WINDINGS.

By MILES WALKER, Member.

(*Paper received October* 27, 1909, *read in London on March* 10, *and at Manchester on March* 8, 1910.)

The paper deals with the currents which flow when large electric generators are short-circuited. Oscillograph records are given showing the current which flows when a 5,500-k.w. generator is short-circuited at its terminals. The forces operating on armature windings are approximately calculated, and the methods adopted by various designers to support armature windings are illustrated. The phenomena accompanying the short-circuiting of direct-current generators and rotary converters are also considered, and oscillograms are given showing the current on short circuit and the voltage rise across the circuit breaker.

ALTERNATE-CURRENT GENERATORS.

Value of Armature Current on Short Circuit.—If the armature of an alternator of ordinary regulating qualities is short-circuited while it is at rest, and the machine is then run at full speed and fully excited, the current in the armature will not rise to more than 2½ or 3 times its full-load value. The reason of this is that the current lags almost 90° behind the phase position of the pole-centre, and it demagnetises the poles. This current would not be sufficient to bring into play any serious forces on the armature winding. But if an alternator while running at full speed and fully excited is suddenly short-circuited at the terminals of the armature, the current may rise to more than 20 times its full-load value. The first rush of current is propelled by the full E.M.F. of the generator, for there is no time in the first $\frac{1}{100}$ part of a second for the field to be demagnetised. The rate at which the current rises is determined by the self-induction of the armature winding, and it is also to a certain extent affected by the distributed capacity between the winding and the frame. In considering the self-induction which is effective immediately after a short circuit, we must take only that part of the self-induction of the armature winding which is due to the flux leaking between armature and field windings.

The rate of the rise of the current is at first but little affected by

the change of magnetic flux through the field magnet, because as the current in the armature rises, there is an eddy current in the pole-face, or even in the field winding itself, which maintains the flux from the pole almost at its full value. It is only as this eddy current dies down that the armature demagnetises the field.

Now, the magnetic flux which leaks across the armature slots and around the end connectors due to full-load current is often in turbo-generators only 5 per cent., and sometimes only 3 per cent., of the total flux from the poles, so it comes about that the rate of rise of the current in one of the phases which happens to be near its maximum E.M.F. at the instant of short circuit would, if the pole-flux were constant, be 20 or 30 times as great as the rate of rise from zero at full load.*

This, of course, assumes that the resistance and self-induction of the path of the eddy current in the pole is negligible. In practice these quantities must be taken into account.

Let us take a case and consider the actual values that one finds in practice. A 5,500-k.w. 3-phase generator with 4 solid salient poles revolves at 1,000 revs. per minute. The total flux per pole amounts to 78,000 kilolines; there are 27 conductors per phase per pole, and the instantaneous value of the E.M.F. generated in phase A at the moment when the pole is in the position shown in Fig. 1 is 9,000 volts. The resistance of phase A is 0·056 ohm. The magnetic flux l_1 which leaks across the slots and around the end windings of the machine when 1 ampere passes in phase A, amounts to 6·2 kilolines per pole. For full-load current—288 amperes (= 405 amperes maximum)—the leakage therefore amounts to 2,500 kilolines, or 3·2 per cent. of the total flux per pole.

Rate of Rise of the Current.—Now let phase A be short-circuited at the moment when the pole is in the position shown in Fig. 1. There is an E.M.F. of 9,000 volts tending to drive current through phase A. As the current rises it will not only set up leakage l_1, but it will create a magneto-motive force in all such paths as m, m, threading through the path of the iron pole. As soon as any flux begins to grow in the path m, m, it immediately produces a current in the pole-face of an amount almost equal to the total current in

* In order to simplify matters the figures given in the paper for the flux per pole are reduced to allow for the breadth coefficient. The leakage flux is treated in the same way. Thus if N is the effective flux (that is the flux multiplied by the breadth coefficient) per pole, then—

$$\text{Volts per phase} = 2 \pi n \text{ N S} \times 10^{-8}$$

where S stands for the turns per phase.

Now if the effective leakage flux per pole for full-load current is $\frac{N}{20}$ it will take 20 times full-load current to set up a reactance voltage equal to the impressed voltage. As will be seen later, the above is not a full statement of the matter. The effective leakage (counting that due to the pole-face) is in practice more nearly $\frac{N}{10}$, but the current may rise to 20 times full-load value through the doubling effect caused by the switching on. See Footnote, page 299.

the phase-band A and opposite to it in direction. In the case in Fig. 1, with counter-clockwise rotation of the N pole, the current in the phase-band A will flow towards the observer from the paper; the eddy current in the pole will flow from the observer towards the paper. The return path for this eddy current will be along the sides of the pole and back along the face of S poles. This current opposes the creation of flux along the path *m, m*, so that the flux cannot grow at a greater rate than is just sufficient to generate the eddy current against the opposition of the resistance and self-induction of its path. As the flux along *m, m* grows it will set up a back E.M.F. in phase A, so that the effect will be just as if the resistance and self-induction of the eddy-current path in the pole were transferred to phase A. The value of the resistance and coefficient of self-induction of the

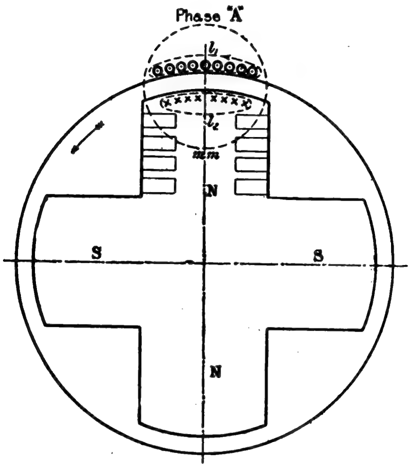


FIG. 1.

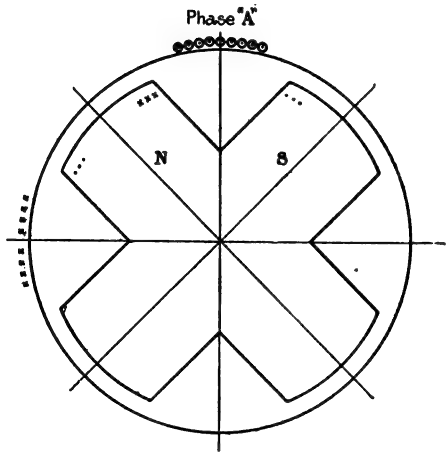


FIG. 3.

Showing Eddy Currents in the Pole-face and the Paths of the Leakage Flux l_1 and l_2.

eddy-current path in the pole would be difficult to calculate in any particular case, but in the case considered below, the coefficient of self-induction (the more important term), when multiplied by the ratio of transformation, appears from the result of experiment to have a value equal to about 2·4 times the coefficient of self-induction of that part of the armature winding which lies opposite the pole. We therefore have the leakage $l_1 + l_2$ as the main controlling factors in determining the rate at which the current *c* in phase A begins to rise; taking $l_1 + l_2$ in the above case to be 2·12 kilolines per ampere, the rate at which the current would begin to rise is 800,000 amperes per second.

Fig. 2 shows generally the way that one would expect the short-

circuit current to. rise, leaving out of account the effect of the distributed capacity. The zero line of the current curve will depend upon the instant at which the switch closes (see note, page 299). The figure also shows to the same scale the full-load current lagging 90° behind the pole-centre. As the pole gets past the middle position, the E.M.F. begins to sink and the resistances of the paths begin to make themselves felt when the current reaches several times its full-load value. As the pole moves round from the position shown in Fig 1 the eddy current moves along the pole-face as though it were a reversed reflection of the

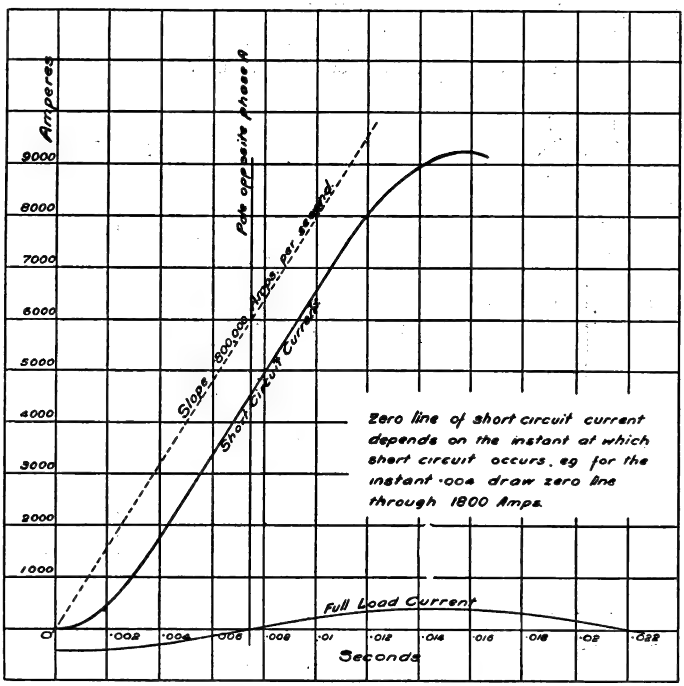


FIG. 2.—The Magnitude and Phase of the Instantaneous Short-circuit Current as compared with Full-load Current lagging 90°.

current in the phase-band A mirrored in the face of the pole, and shortly after the corner of the pole has left phase A, there is an eddy current in the pole-face down one side and up the other, which tends to keep up the flux in the pole against the strong demagnetising current in phase A, which is now in the best demagnetising position (see Fig. 3). In a polyphase machine the cross-magnetising and the demagnetising effects occur at the same time, but in Figs. 1 and 3 we have only considered phase A.

If instead of a solid pole we have a laminated pole, the resistance

of the path for the eddy current is very much higher, but it is found that the exciting current in the winding is increased at the instant of short circuit, and takes the place of the eddy current in keeping the value of the pole-flux nearly constant for the instant after short circuit. By the time that the pole S comes under phase A the eddy currents are beginning to diminish, so that pole S is not as strong as pole N was. Though the current may fall under the influence of pole S, it does not always cross the zero line, but rises again under the influence of the next N pole, so falling and rising, and describing a waving line which keeps its mean value above the zero line for several alternations. It may be said that at the instant of short circuit a direct current is generated in the winding which is maintained by the self-induction of the winding and slowly killed by the resistance. Superimposed on this direct current is an alternating current generated by the passing of the poles alternating N and S, and at the same time gradually growing weaker as the eddy current in the pole-face or in the exciting windings grows weaker. After a few seconds the poles become normally excited and the current sinks to two and a half or three times its full-load value.* In order to ascertain the instantaneous value of the current in the armature at the time of short circuit, some records were taken on a

* There is a difficulty in dealing with this subject analytically, because the eddy paths in the poles are not of simple form, and their resistance and self-induction vary somewhat as the eddy current takes up different positions in the poles. We know, however, that there is produced at the instant of short circuit a large magnetising eddy current. We also know that the magnetising eddy tends to live by reason of the self-induction of its path, but is slowly killed by the resistance of the path, so that we may assume that it changes with time t' approximately as the expression $C_e \, \varepsilon^{-\frac{r_2}{l_2} t'}$ where C_e is its maximum value, and r_2 and l_2 are the values of the resistance and coefficient of self-induction of the path, so far as these are capable of being expressed by constants. Now the E.M.F. in the armature at any instant may be regarded as consisting of two parts: one part e_s, the E.M.F. which is sufficient to drive the final short-circuit current through the armature against its resistance and self-induction, and the evanescent part e_e, the E.M.F. generated by the flux from the pole which is produced by the eddy current in the pole.

$$e_s = E_s \sin 2 \pi n t$$

$$e_e = \varepsilon^{-\frac{r_2}{l_2}(t-t_1)} E_e \sin 2 \pi n t$$

Here we have written $t' = (t - t_1)$ in order to have only one time variable. t_1 is the time at which the switch is closed.

At the instant of short circuit $(t - t_1) = 0$, and $e_s + e_e = e$, the full E.M.F. of the machine. As the eddy current in the pole dies out e_e disappears and $e = e_s$, and the machine then gives its normal short-circuit current. The expression for the current at any instant after a short circuit therefore takes the form—

$$C = \frac{E_s + \varepsilon^{-\frac{r_2}{l_2}(t - t_1)} E_e}{\sqrt{r_1^2 + 4 \pi^2 n^2 l_1^2}} [\sin (2 \pi n t - a)]$$

$$- \frac{E_s + E_e}{\sqrt{r^2 + 4 \pi^2 n^2 l^2}} \varepsilon^{-\frac{r_1}{l_1}(t - t_1)} (\sin 2 \pi n t_1 - a).$$

The last term of this expression corresponds to the evanescent term which always appears in the expression for the current after switching on. As t_1 is a constant, the last term represents a current, which is always on the same side of zero, possibly very

Duddell oscillograph fitted with a cinematograph film. Fig. 4 shows one of these records taken on a machine of the type shown in Fig. 1. The curve V shows the voltage before the short circuit, which in this case is 3,900 virtual, the maximum point being 5,700 volts. At the instant of short circuit the voltage at the terminals of the machine falls to zero and the current curve springs into being; the highest current recorded was 3,100 amperes. The curve is sufficient to show the general nature of the current on short circuit. It will be seen, as indicated in Fig. 2, that it rises to such a high value during the first half of a cycle that the pole which passes during the next half cycle is barely sufficient to bring it to zero. It then rises and falls in waves of gradually diminishing amplitude, until after a lapse of several seconds it assumes the value it would have had if the short circuit had been made before the field was excited. The value of the current at the first peak is in this case 7·6 times as high as the maximum value of the current after it has settled down. Therefore if the normal short-circuit current of the machine is taken at three times full-load current, the instantaneous short-circuit current would be—

$$7{\cdot}6 \times 3 \times 1{\cdot}41 = \text{about } 32 \text{ times full-load current.}$$

In order to get a better idea of the decrement of the wave of current, the oscillograph shunt resistance was changed so that the instrument would draw the smaller end of the curve on a larger scale. This is shown in Fig. 5. In this case the peak of the current curve on short circuit is completely off the film, and it is only after several alternations that the amplitude is sufficiently diminished to bring the tops of the waves into view again. The film was stopped for several seconds to allow the armature current to assume its final value. This was 295 amperes as recorded on an ampere-meter. It will be seen from this curve that even the 24th wave after the short circuit is 60 per cent. higher than the wave after it has settled down.

Figs. 6, 7, and 8, show the current curve drawn to a different scale again. The peak in some cases is still off the film, but from Fig. 8 a good idea can be obtained of the rate of decrease of the pole-strength. Figs. 6 and 7 are interesting because they show the effect due to the capacity of the winding. At the instant of short circuit, the current

great at the instant of switching on, and slowly dying as it is killed by the resistance of the armature winding. The angle α, of course, equals $\tan^{-1} \frac{2 \pi n l_1}{r_1}$.

The following are the values of the different quantities as calculated from the curve in Fig. 6—

$E_s = 975$ volts (maximum in one phase).
$E_e = 2740$ volts (maximum in one phase).
$r_1 = 0{\cdot}105$.
$l_1 = 0{\cdot}011$.
$\frac{r_2}{l_2} = 2{\cdot}06$ during first half-second, but changes slowly to $1{\cdot}15$.
$n = 33\frac{1}{3}$.
$t_1 = 0{\cdot}002$; t is taken so that the volts of one phase of the generator $= 3{,}715 \sin 2 \pi n t$.

appears to rise almost perpendicularly and sink again in less that $\frac{1}{1000}$ of a second. It then rises on the curve which we have already considered, that curve being more or less distorted by an oscillation due to the capacity of the winding.* It does not appear from these curves—which were obtained when the machine was short-circuited at a maximum of 7,000 volts—that the rush of current due to the capacity of the winding is greater than the current shown by the peak of the smooth wave; but it may be that under certain conditions, and at higher voltages, this condenser current may rise to a higher value than the armature current restrained by its resistance and self-induction would rise to.

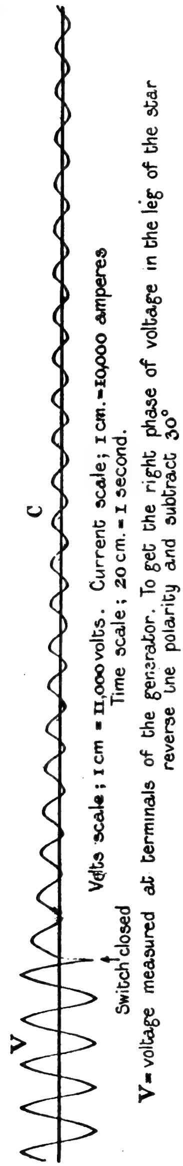


FIG. 4.—Oscillograph Record of Armature Current when an Alternator is Short-circuited.

Volts before Short Circuit = 3,900 Virtual. Maximum Current, 3,100 Amperes.

The capacity of one phase of the winding to earth was only 0·028 microfarad. The maximum voltage to which the terminals were charged in the experiment illustrated in Fig. 8 was only about 4,000 volts. The voltage to earth may be taken as varying at different points of the winding from 0 at the star-point to 4,000 volts at the terminals. The stored energy under these conditions would only be one-third of what it would be if the whole winding were charged above earth. This stored energy would be about—

$$\tfrac{1}{3} \times \tfrac{1}{2} \times 0{\cdot}028 \times 10^{-6} \times 4{,}000 \times 4{,}000$$
$$= 0{\cdot}075 \text{ joule.}$$

This is not sufficient energy to do much harm to the coils.

Eddy Currents in the Pole.—Two interesting phenomena arose out of these experiments. It was noticed that the instant the oil switch was closed which connected the terminals of the armature together, a ring of flame appeared at the ends of the field magnet. This flame was the more mysterious because the field magnet was flanked with a heavy bronze end bell at each end, and the ring of flame appeared on the face of this end bell, and had a diameter about 4 in. less than the bell itself. On inspection it was found that the bolts, at a distance of 2 in. from the circumference, which held the bell to the field

* See discussion where doubt is thrown on the origin of these ripples.

magnet, were pitted where they pressed upon the bronze. The explanation appeared to be that the eddy current in the pole-face was so enormous that in passing to the end bell on its way to the next pole it made an arc between the bronze bell and the steel bolts. No

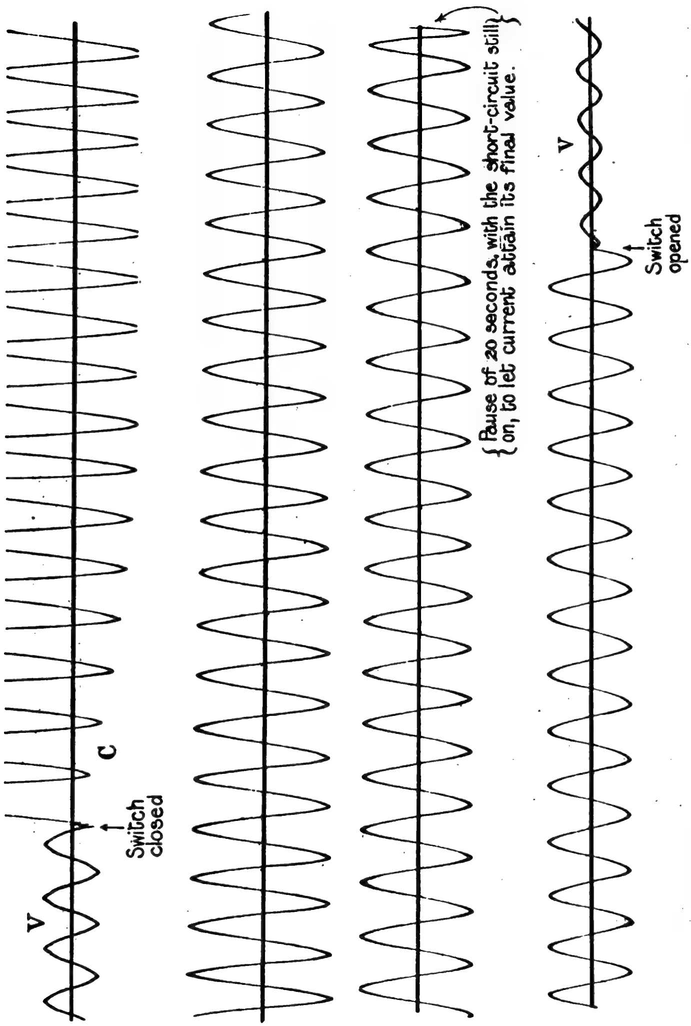


FIG. 5.—Oscillograph Record of Armature Current on Short Circuit, showing rate at which the Current decreases, and also the Way in which the Voltage increases after the Short Circuit is Removed.

Scale of Current, 1 cm = 800 Amperes.

one, without seeing it, would have believed it possible. The value of the eddy current can be roughly calulated, because we know that it is almost equal to the current in the armature wires, multiplied by the number of wires opposite the pole-face—in the case of these experiments about 150,000 amperes.

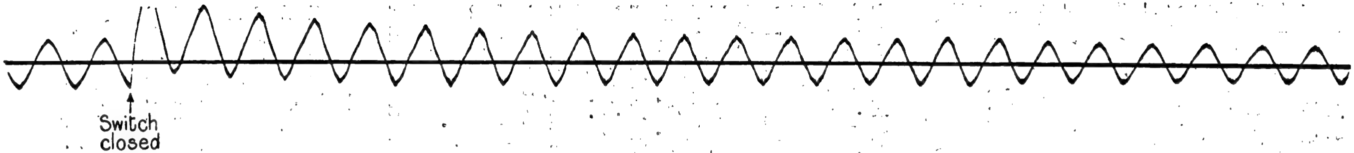


FIG. 6.

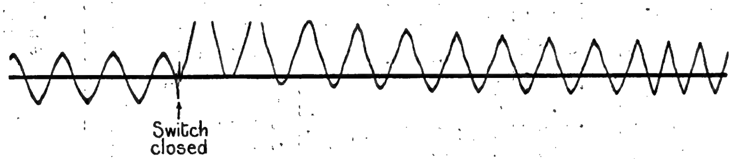


FIG. 7.

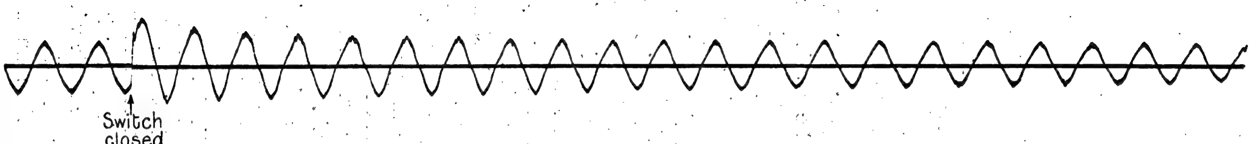


FIG. 8.

Showing the Different Behaviour of the Short-circuit Current depending on the Particular Instant at which the Switch is Closed.

(In Fig. 8 the switch is closed when the voltage in the leg of the star is at its maximum, we therefore get an almost symmetrical curve for the current. The capacity effect is apparent in all three curves and produces marked oscillations in Fig. 8.)

Behaviour of Exciting Current.—Another remarkable thing was the behaviour of the ampere-meter in circuit with the field magnet. From experience with other machines, one would have expected the field current to rise after the short circuit. An increase in the current is easily understood when we remember that the armature suddenly applies a demagnetising force, and any diminution of the magnetism of the pole creates a forward E.M.F. in the field winding which does not cease until the pole reaches its final weakened state. In the experiments on the machine with solid poles, however, the effect was reversed.

The field was excited from separately driven exciters feeding bus-bars at 125 volts, the current being controlled by a rheostat. The current before the experiment was adjusted to 70 amperes. For a moment after the short circuit it remained almost stationary, and then quickly fell until it was only about 20 amperes. It then rose above its normal value, and it was not until after 7 seconds that it fell again to 70 amperes.

The explanation of the *decrease* in the exciting current in this case appears to be as follows: At the instant of short circuit an eddy current is produced in the solid metal of the pole itself and this screens the field winding from any inductive action during the first second. The eddy current is produced on the surface of the pole but gradually sinks into the body of the pole; the path of the current has now a coefficient of self-induction which is fairly great as compared with its resistance, because the magnetic lines produced by the eddy current lie in short closed paths in the iron of the pole. This eddy current in a path of such low resistance and high self-induction can easily subsist several seconds after the armature current has settled down to a small value. Thus after the powerful demagnetising effect of the armature is removed, the magnetising effect of the eddy current still exists, and as it sinks into the body of the pole it takes the place of, or assists for the time being, the normal field current, causing this current to sink in value. In the course of time the resistance of the path kills the eddy current and the field current rises again.

This effect does not occur in a laminated pole. The demagnetising effect of the armature causes the field current to rise at the instant of short circuit.

If a copper damper is placed on the surface of the field magnet the eddy current appears mainly in this, and the field winding is screened more or less according as the resistance of the damper is less or more. In one case where a 1,000-k.w. turbo-generator was short-circuited at full voltage, sparks were seen between certain parts of the metal of the damper which did not make perfect contact, showing that it is very necessary when dealing with the enormous currents which appear in a damper of this kind to see that the joints in the metal are made with the utmost care.

Forces on the Windings.—The study of the instantaneous currents which flow when an alternator is short-circuited is important on

account of the great forces which they bring into play upon the armature windings. In fact, there has been considerable difficulty in the past in devising adequate means of supporting the coils. Even with slow-speed generators, it was known that the sudden rush of current which occurred on short circuit, or when the generator was thrown on the busbars badly out of phase, would injure the winding unless it were made very strong and suitably supported. But it was not until after many serious accidents that the designer realised how many times greater were the forces he had to deal with in the case of turbo-generators. The reasons for the difference in this respect between slow-speed machines and turbo-generators are as follows: In the first place, the high-speed machine has comparatively few poles, and therefore the ampere-turns per pole are very much greater. For instance, a 3,000-k.w. 25-cycle engine-type generator, running at 94 revs. per minute, may have about 2,000 ampere-turns per phase per pole, while a 3,000-k.w. 25-cycle turbo-generator, running at 1,500 revs. per minute, may have as many as 8,000 ampere-turns per phase per pole. The force is proportional to the square of the current, so that four times as many ampere-turns will give us many times as much force even though the coils are broader.

Secondly, the span of the coils in the engine-type machine is very much shorter. In the machines compared above, the spans of the coils might be 18 in. in the one case, and 90 in. in the other.

Then again, the magnetic flux leaking across the slots and around the end-windings bears a much smaller ratio to the total flux per pole in the case of many turbo-generators than it does in the case of engine-type machines. This consideration, as we have seen above, is one that determines the value of the current on short circuit.

The troubles that were experienced in the early turbo-generators were, no doubt, partly due to the disinclination on the part of the designer to bring the high-tension winding very near to metal clamps. Experience had shown that it was desirable to preserve long-creepage distances and to keep coils of different phases as far away from each other as possible; any clamping that had to be done was done in accordance with old-established rules of insulation. The result was that in many cases the clamping was insufficient.

It is interesting to take an arrangement of coils and to calculate what forces are at work on various parts, assuming that the current at the instant of short circuit is 32 times as great as the normal full-load current. Fig. 9 shows the plan of a coil of an old-fashioned winding which was completely wrecked by the throwing of a generator on to the busbars when it was out of step. The direction of the current in the windings is shown by the arrows. Fig. 10 is a diagram showing the intensity of the magnetic field at various parts of the winding along the section A–B, when 1,000 amperes is flowing in each conductor. This diagram has been arrived at by a summation of the values of the field produced by different conductors at every point along the section A–B. It will be seen that the magnetic field

at point C is as great as 530 C.G.S. units. If at this point we have 3 conductors, each carrying a current of 1,000 amperes, the force on the armature coil will be 11·2 lbs. per foot run. Now the force increases as the square of the current: so with 10,000 amperes per conductor (if we add a little for the capacity effect, the current works out at something over 9,300 amperes) the force would be 100 times as great, that is to say, 1,100 lbs. per foot run for the worst coil. Even this great force, if it acted slowly, would not have caused as much bending as had apparently taken place. But when a force acts on a beam quickly, it can produce by the swing double the amount of deflection it can produce when acting slowly. Taking this swinging action into account, the twisting of the coils can be explained. Still the work of the destructive forces in these cases is so startling in its nature that one wonders at times if materials retain their ordinary

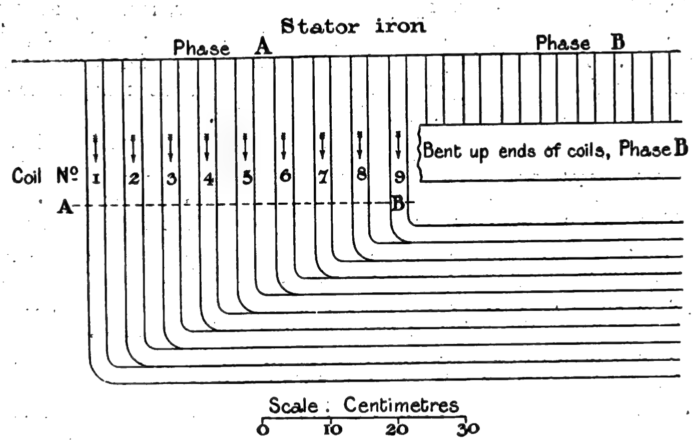


FIG. 9.

mechanical properties when subjected to these sudden electromagnetic forces. For example, some blocks of maple wood having a section 6 in. by 8 in. placed between the bent-up coils and the iron end-plate, were crushed to splinters as if they had been under the blows of a steam hammer. Experiments were made on an insulated coil to see what bending forces it would stand without destruction. The experiments were made on the coil when it was cold, and it was found that the stiffness of the coil was very much greater than the calculated stiffness, taking into account the copper conductors only, showing that the coil derived a great part of its strength from the insulation. This is interesting, because one does not ordinarily expect insulation to have very great mechanical strength. It would have been better had the test been carried out with a warm coil.

Switching in Out of Step.—If two similar alternators running at full speed and fully excited are thrown in circuit with one another when directly out of step, the current which flows through the armature is the same as if each machine had been short-circuited at its terminals. The E.M.F. taken in the whole circuit of the

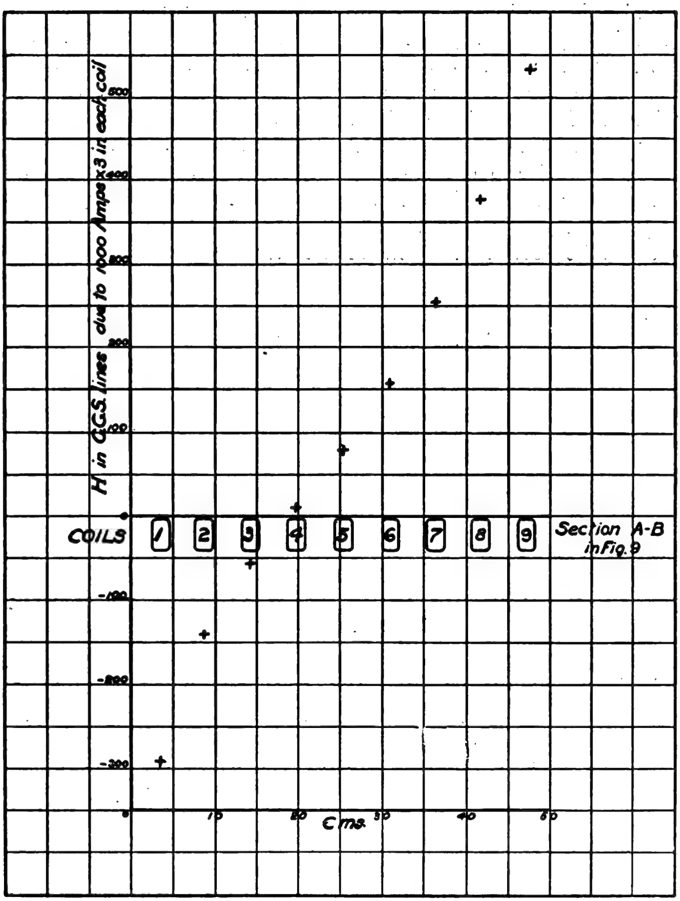


FIG. 10.—Showing Strength of Magnetic Field in the various Coils depicted in Fig. 9 due to 1,000 Amperes in each of the Three Conductors which make up One Coil.

two machines is doubled and the resistance and self-induction are also doubled. If the machines are thrown into circuit only partly out of step, the current which circulates is not so great, being equal to the short-circuit current multiplied by the sine of half the angle of phase displacement between the two machines.

Where two machines are feeding a busbar and a third similar machine is thrown on to the busbar directly out of step, the current flowing in the latter machine will be one-third greater than if it were short-circuited at its terminals. This is because the total E.M.F. in circuit is doubled, while the resistance and self-induction of the circuit are only increased in the ratio of 3:2. Where three machines are feeding a busbar and a fourth is thrown on to the busbar directly out of step, the current is 50 per cent. greater than if the machine were short-circuited at its terminals; and so on, as the resistance and self-induction of the machines in circuit with the busbar become less and less. The maximum effect will be obtained where a machine is switched on to a busbar fed by a very large number of generators. In this case, the current might rise to almost double the value it would attain on a dead short circuit; *i.e.*, the forces which would come into play would be nearly four times as great.

It will be seen that when we are dealing with forces of many

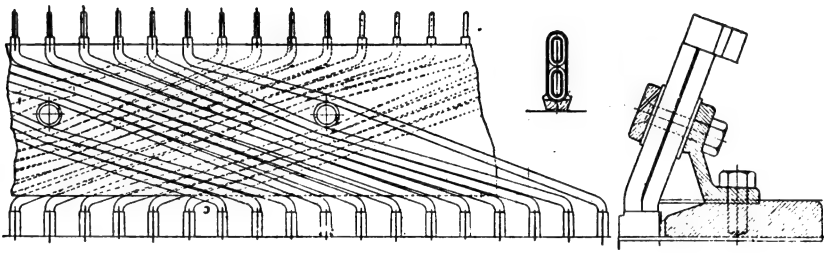


FIG. 11.—Barrel Winding of Stator supported by Internal Ring of Metal bolted to Brackets.

hundreds of pounds per foot run, especially when many coils are grouped together, very strong clamps are necessary to keep the windings in position. The old plan of tying coils together with torpedo twine and securing them with wooden blocks is wholly insufficient. One cannot hope to make a satisfactory construction without using strong metal clamps. This necessitates insulating the whole of the winding outside the slots with an insulation which is not only strong enough to withstand the whole testing pressure, but is of such a good mechanical nature that it will not be crushed under the pressure of the clamps.

It is convenient here to consider the various types of end connectors which are commonly employed on the windings of turbo-generators.

There is first the barrel winding, in which all the coils are of the same shape and fit against one another, forming a continuous latticework (see Fig. 11). The advantage of this type of winding is that the field produced by some of the conductors is to a certain extent neutralised by the field produced by conductors lying near, so that

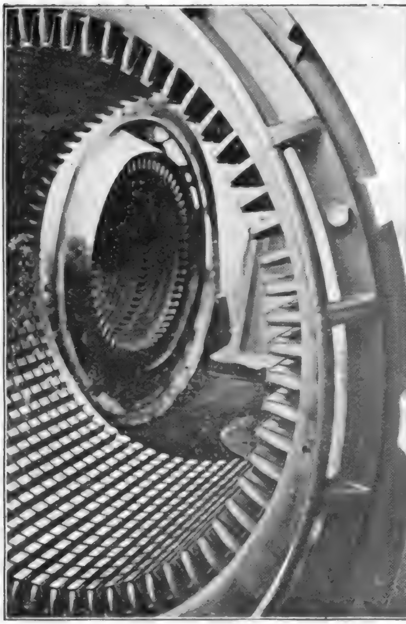


FIG. 12.—Cast Metal Ring for supporting Winding (British Thomson-Houston Company).

FIG. 13.—Method of Bracing Coils to Cast Metal Supporting Ring (British Thomson-Houston Company).

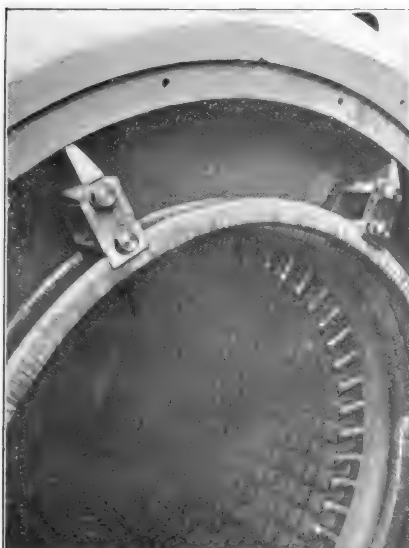


FIG. 15.—Insulated Supporting Rings.

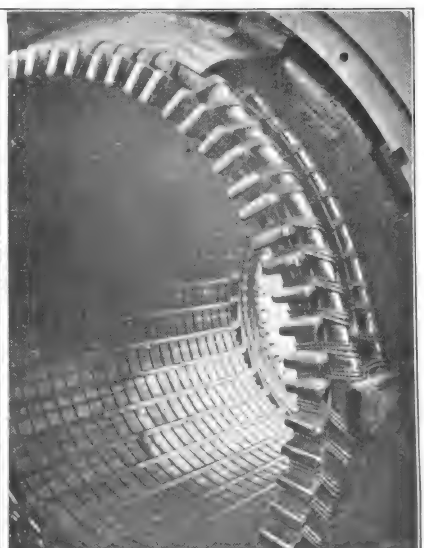


FIG. 16.—Method of lashing Rings to Bar Winding (British Thomson-Houston Company).

the magnetic field over a great part of the coils is not as great as with other types of winding. The magnetic field, however, at the point *c* in Fig. 11, is as great as with any other type and, at this point, the coil is difficult to support. With this winding the conductors belonging to different phases lie next to one another, and it is very necessary to insulate the coil throughout its whole length with insulation strong enough to resist full pressure to earth. It is usual to impregnate the coils as a whole and to place them in open slots, the coil being secured by wedges in the top of the slot. Various methods are employed to secure the parts of the coils lying outside the slots. One very good method, employed by the British Thomson-Houston Company, is

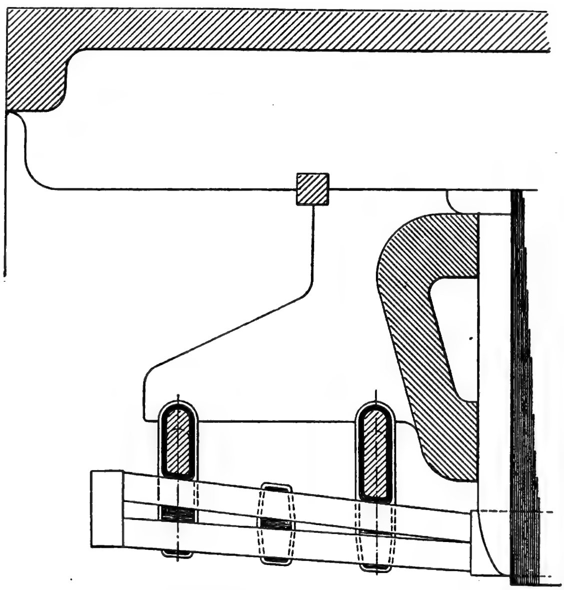


FIG. 14.—Supporting Rings for Barrel Winding (British Thomson-Houston Company).

shown in Figs. 12 and 13. A very substantial ring, supported on brackets, and cast with them, is provided immediately behind the winding. This ring is well insulated and the formed winding is braced to it by means of circular metal bands placed over wooden clamps which are shaped to hold the coils. Figs. 14, 15, and 16 illustrate another method employed by the same firm for securing a barrel-wound armature. Here there are two rings wound with a considerable thickness of insulating material and held by brackets cast with the frame. These rings have some portions cut away, and it is thus possible to put them into the notches in the brackets, and after turning them through a small angle on their principal axis, to lock them at a point where the

diameter is rather larger. The winding is then put into the slots and braced to the insulated rings, as shown in Figs. 16 and 17.

Another type of winding is shown in Figs. 18 to 23. In this case the coils are concentric and are placed in 2 or 3 ranges, each phase being separated from its neighbour, and in addition to the insulation on the coils thick insulating blocks can be placed so as to separate all points between which a high voltage exists. This winding has the following

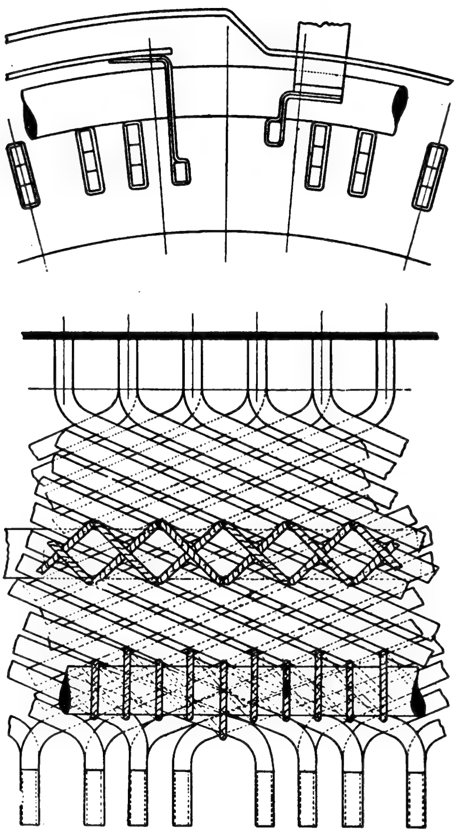


FIG. 17.

advantages: The part of the coil lying in the slot can be made of perfectly straight conductors insulated with mica, or mica and paper impregnated and compressed so as to exclude all air from its composition. These operations can be much more satisfactorily carried out on a straight coil. After the straight part is placed in the slots, the ends can be connected by connectors which have been previously insulated, and the insulation of the joints can be carried out with tape and

varnish in a thoroughly satisfactory manner. If ever it should be necessary to make a repair on the machine, a coil of this kind can be taken out of the slot without interfering with the rest of the winding. The end connectors, which are subjected to the great forces on short circuit, can be made of much thicker material than the remainder of the coil, and the shape of the section may be so designed as better to resist the mechanical forces. However strong the conductors themselves may be, reliance must mainly be placed on strong metal

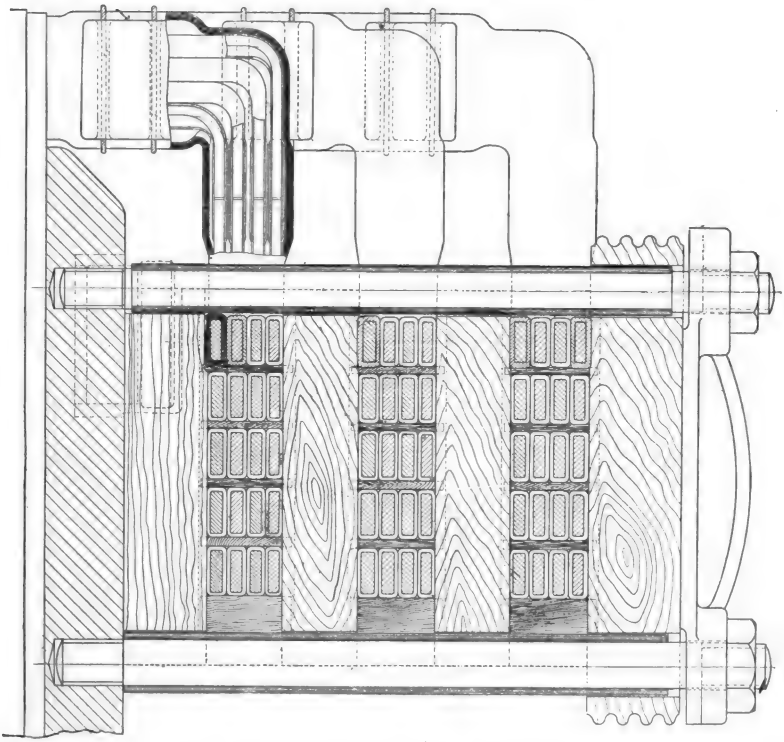
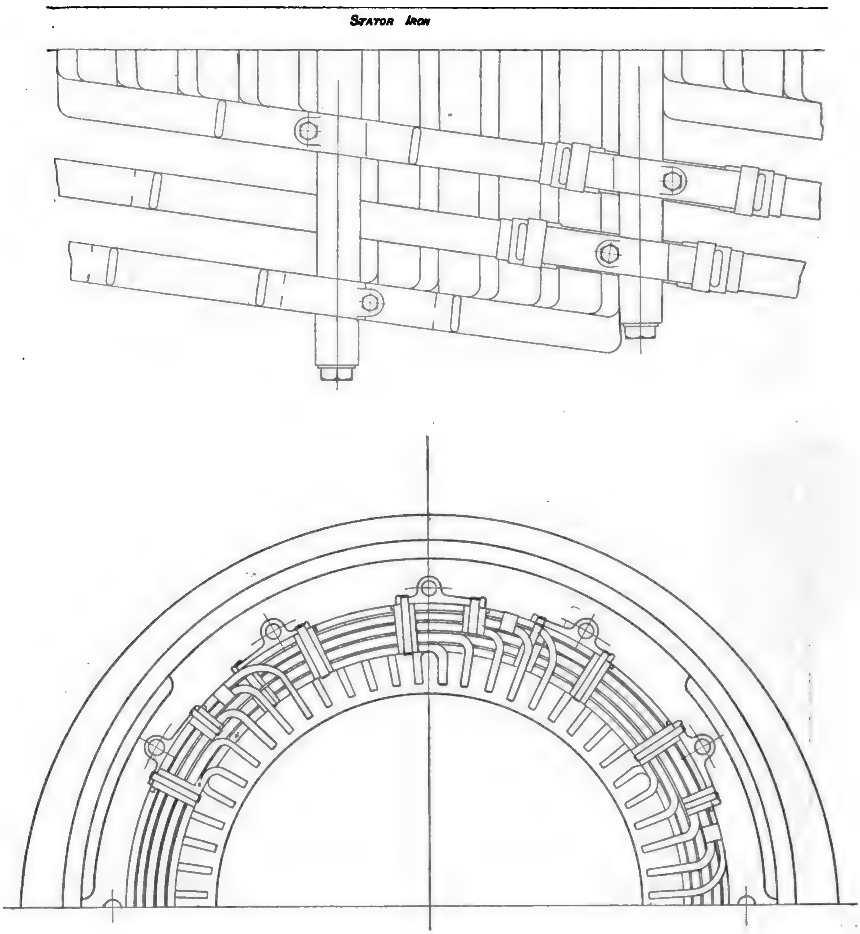


FIG. 18.—Concentric Coil Winding in Three Tiers made with Rectangular Strap and Bolted to End Plate (British Westinghouse Company).

clamps to resist forces due to a dead short circuit. Cases are on record where even the clamps, held by 1 in. studs, have been forced out of position and the winding wrecked. The clamps shown in Fig. 18 are made by screwing bronze bolts into a cast-steel end-plate, a metal beam of a section designed to resist great forces is screwed down by means of nuts on the winding, and the various ranges are separated by hard wood blocks. In addition to the blocks between the ranges, wooden blocks are secured between the coils on those parts where

they emerge from the slots and also on the corners. Experience has shown that a winding of this kind, if carried out according to the best practice, is able to withstand repeated short circuits without any budging of the coils.

Fig. 18 shows the winding on the 6,000-k.v.a. 11,000-volt generators



FIGS. 24 and 25.—Imbricated Winding with External Clamps.

of the Underground Electric Railways Company at Chelsea. This winding replaces the older winding shown in Fig. 9. It has been in service for four years, and has not given any trouble either from want of insulation or from distortion due to excessive mechanical strains. Fig. 19 shows the winding of the 6,000-k.v.a. generators built for the

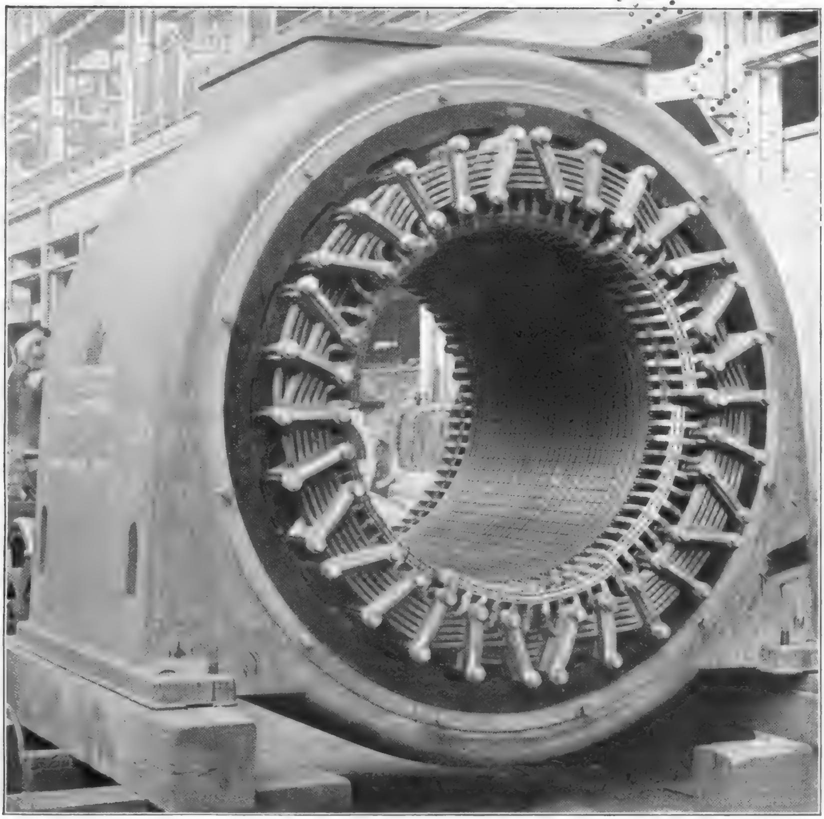


FIG. 19.—Winding of 6,000-k.v.a. 3-phase Generator (British Westinghouse Company).

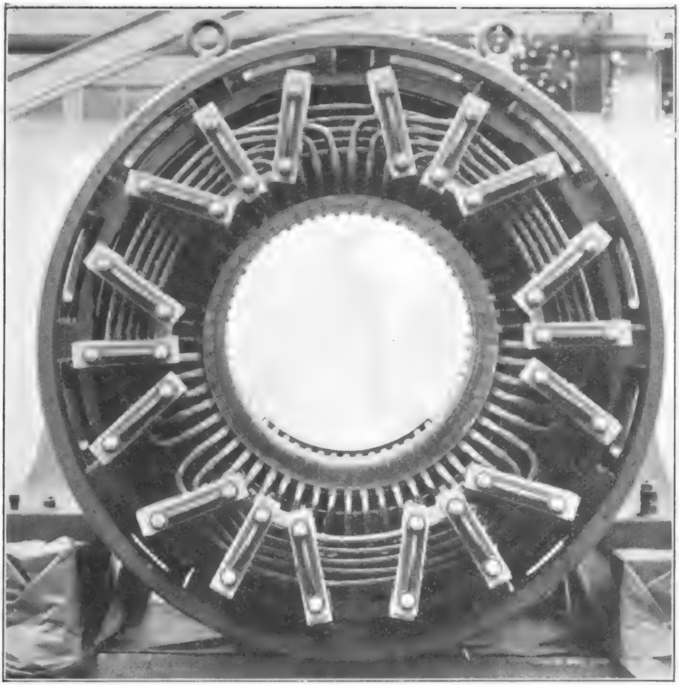
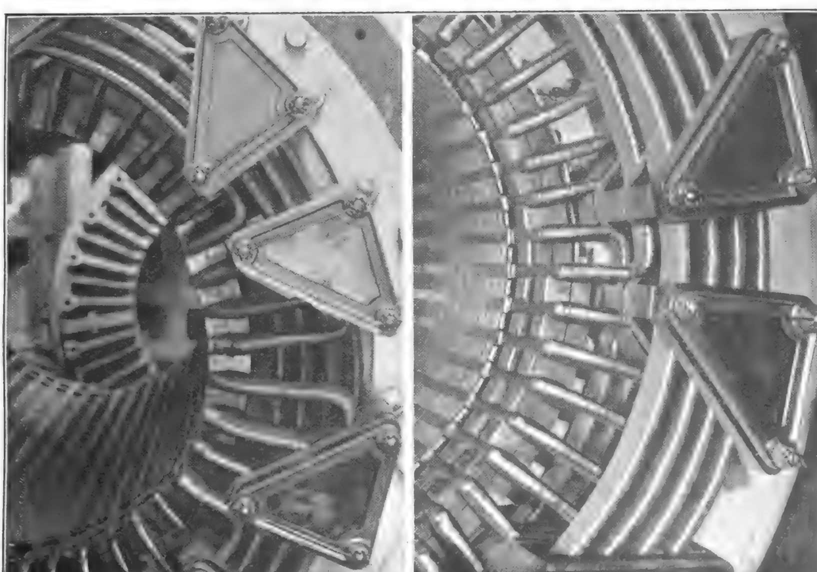


FIG. 20.—Bracing on Armature Winding (Bruce Peebles & Co.).



FIGS. 21 and 22.—Triangular Clamping Blocks on Winding of 2,000-k.w. 25-cycle Generator, 5,500 Volts (Brush Electrical Engineering Company).

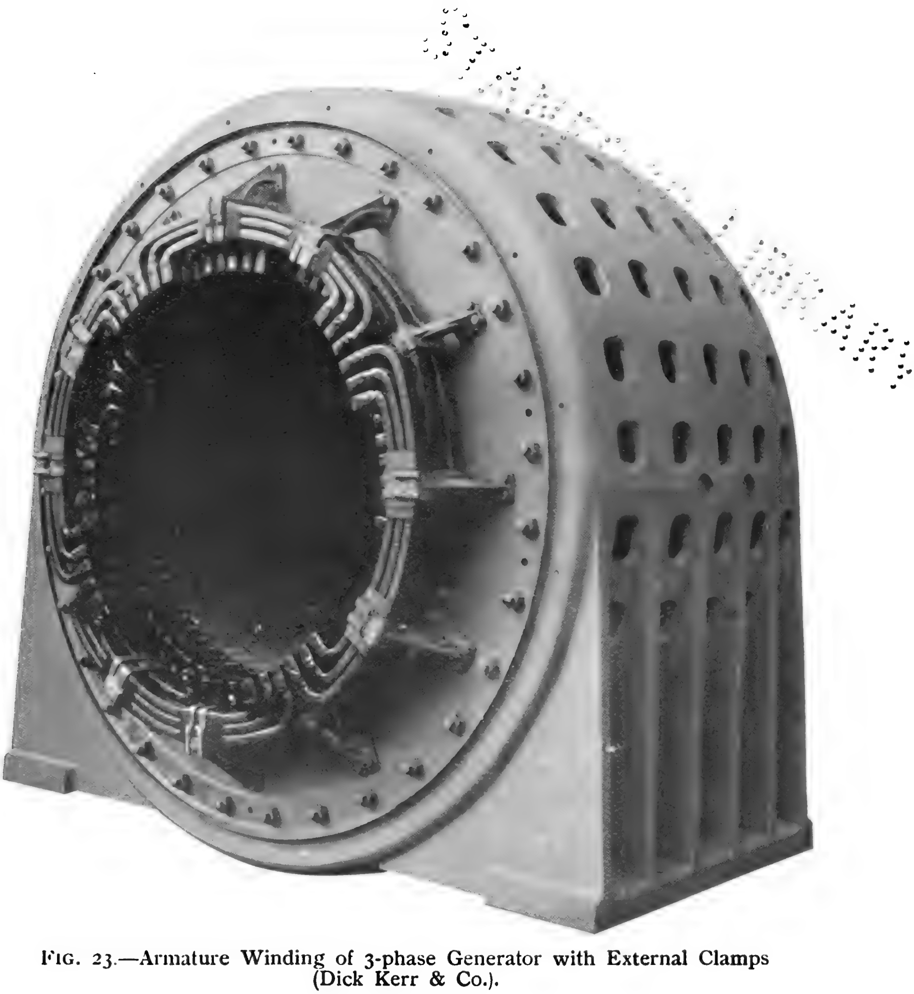


FIG. 23.—Armature Winding of 3-phase Generator with External Clamps (Dick Kerr & Co.).

London County Council. It is of the same type as Fig. 18, except that there are only two ranges instead of three. It illustrates well one of the latest methods of supporting armature coils.

Fig. 20 shows a turbo-generator by Bruce Peebles & Co., also with coils in two ranges and fitted with stong clamps. Figs. 21 and 22 give two views of winding of a 2,000-k.w. 25-cycle 5,500-volt turbo-generator built by the Brush Electrical Engineering Company. Here the clamps are made triangular in shape, and held by three studs. Fig. 23 illustrates a winding by Dick Kerr & Co., which has been very successful in operation.

The winding illustrated in Figs. 24 and 25 is of a rather different type. Instead of having two or three distinct ranges lying in different planes, the coils are placed obliquely and are imbricated one over the other. When secured by suitable clamps this winding can be made very strong and satisfactory.

It is probable that when we come to build machines of much larger

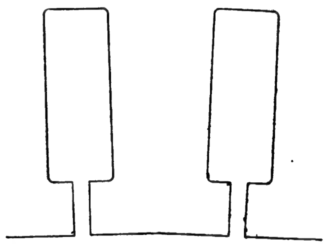


Fig. 26.—Armature Slot made with very Broad Lips in Order to Increase the Leakage and Lessen the Short-circuit Current.

output and of few poles we shall be compelled (in addition to providing the strongest clamps possible) to restrict the current, the short-circuit current, by keeping down the ampere-turns in the field magnet, or by artificially keeping up the value of the self-induction of the winding. It is possible to keep down the ratio of field ampere-turns to armature ampere-turns, and yet secure extremely good regulation by adopting a suitable distribution of material in the machine.

In order to increase the self-induction of the winding we may employ choke coils in series or we may increase the armature leakage by employing slots with semi-closed mouths and very deep lips as illustrated in Fig. 26.

In designing the winding for a turbo-alternator, the following considerations must be kept in view:—

1. The insulation is of the first importance, and nothing must be introduced which will cause a surface creepage, even after the winding has become dirty.
2. There must be plenty of space left for the circulation of air.

3. The conductors themselves must be sufficiently stiff to resist the forces which come into play between clamps.
4. The clamps must be sufficiently close together, and sufficiently rigid to resist the enormous forces which come into play on short circuit.
5. It is desirable, if possible, to arrange the coils so that one can be taken out without disturbing the rest of the winding.
6. Where the machine is of such a size that the forces on the coils would be so great as to endanger the windings some device must be introduced to limit the current in case of an accidental short circuit.

Short-circuiting of Direct-current Generators.—When a direct-current generator running at full voltage is short-circuited at its terminals the current at first may reach an enormous value, but as the poles become weakened by the cross-magnetising effect the current falls. This is particularly so in the case of a shunt-wound generator. A series-wound generator can be made with very low saturation and a strong series winding which would maintain an enormous current until it pulled up the prime mover. In most series-wound generators, however, saturation sets in comparatively early, and the cross-magnetisation and the resulting saturation of the armature teeth cuts down the voltage to a low figure after twelve or fifteen times full-load current is reached. The first rush of current, however, is limited only by the self-induction and resistance of the circuit, just as in the case of an alternate-current generator, and it may reach thirty or forty times full-load value.

The harm done by currents in the case of direct-current machines has mostly been confined to the breaking of shafts, the leaping of cables from their supports, in the flashing over and burning of the brushes and commutator, and in the breaking down of insulation in the various parts of the system. It is not often that the armature winding is injured, because the current is divided up between a number of parallel paths and the armature coils in the end windings lie close against one another, and cannot be moved very far by the attractions and repulsions which occur.

The twisting-off of the shaft was a common accident in the early days of traction-generators. The modern practice of bolting the fly-wheel direct to the armature, and special designing of the shaft to stand a short circuit has reduced the number of accidents of this kind.

The leaping of cables is familiar to all old dynamo testers, and should always be seriously considered as one of the things which may happen in the case of a short circuit.

One case occurred within the experience of the author on a short circuit of a 500-k.w. 500-volt direct-current generator. The current from the machine was carried by two lead-covered cables, 2 in. outside diameter, weighing about 8 lbs. per foot. The current went out along one cable and returned by the other. The cables were laid

on a shelf in a subway about 6 in. apart. When the short circuit occurred, the cables repelled one another with such great force that they flew apart and struck the walls of the subway on each side, one cable being thrown to the floor the whole length of the subway. It would probably take an initial force of 40 lbs. per foot run to give such a great acceleration of the cables. Now the full-load current of 1,000 amperes would only produce a force of 0·09 lb. per foot run between the cables. It would take twenty times full-load current to produce a force of 36 lbs. per foot run.

Sometimes cables irregularly coiled on the test-plate will, under the action of these enormous currents (and possibly also from the action of opposing currents induced in the test-plate), spring up into the air like snakes, and may easily lead to other accidents.

Flashing over between the brushes on direct-current generators and rotary converters in the event of a short circuit seems to be due to two causes, either of which may be the predominating factor in any particular case. One case is the failure of the machine to commutate the excessive load, and the other is the rise of pressure which occurs when the circuit breaker opens.

If a machine fails to commutate, the arc between the commutator bars and brushes becomes drawn out as the commutator revolves, until it creates an arc between positive and negative brush-holders. Sometimes a spark under the brushes still keeps alight as a spark between commutator bars, and when the bars moving away from the neutral-point have a fairly large voltage between them these sparks grow into big arcs which combine together and form a single arc extending from brush to brush. This short circuits the field windings, and the voltage dropping, the arc most commonly goes out without doing more injury than pitting the brush-holders and the commutator.

The opening of a circuit breaker carrying a heavy current is accompanied by a rise of pressure due to the self-induction of the series windings or the self-induction of the cables. The effect is sometimes made worse by the peculiar properties of the arc which occurs on the circuit breaker. Steinmetz has shown * that when the capacity and self-induction of the circuit in series with an open arc in air have certain values, the rise in pressure may be measured in thousands of volts. Cases are not uncommon where on a 500-volt circuit the opening of the breaker has caused a discharge to occur through an air-space showing a rise of pressure of from 10,000 to 20,000 volts. In one case within the experience of the author, a 500-volt direct-current generator, when a short circuit was interrupted by the breaker, flashed over from the series coils to the frame through a distance of $\frac{5}{8}$ in. In another case, the circuit breaker on one of the feeders supplying the North Eastern Railway opened on a short circuit occurring on the line, and the self-interrupting property of the arc in air of which Steinmetz speaks was so effectual and sudden that the current in the feeder arced

* *Journal of the American Institute of Electrical Engineers*, vol. xviii., p. 385 (1901).

across from a stud on the back of the switchboard through a distance of 4 in. over a dry marble surface. Other cases are on record of arcs being created between one part of a switchboard panel and another under circumstances which show beyond doubt that when the conditions are suitable, enormous rises of pressure may occur. It will be interesting to hear the experiences which members of the Institution have had of cases of this kind. Unfortunately it is very difficult to make the phenomenon occur when we wish to experiment upon it. A generator or a rotary converter of large capacity seems to be necessary to produce the effect, and the effect may often be due to some accidental occurrence in the arc of the circuit breaker itself.

The Underground Electric Railways of London kindly put at the disposal of the British Westinghouse Company an 800-k.w. 600-volt rotary converter in Baker Street Sub-station for the purpose of experimenting on this phenomenon. Fig. 27 gives a diagram of the connections which were made. A Duddell oscillograph was arranged to record the voltage either across the points A, B, C, or D at will, and at the same time record the current passing in the feeder. A cinematograph film was used running at a speed of 25 in. per second. In the current curves C, Figs. 28 and 29, a deflection of 1 in. corresponds to 25,000 amperes in the feeder. For the volt curve, a deflection of 1 in. represents 1,750 volts. Adjustable spark-gaps were placed across the points V, W, X, Y, Z.

A great number of experiments were made, but only a few of them are of interest in this paper. In some of these the current was limited by means of an iron rack placed in circuit with the feeder. At 2,750 amperes, 5,800 amperes, and 8,000 amperes, nothing remarkable happened ; on only one occasion was any spark observed at the spark-gaps on the opening of the circuit breakers. On this occasion sparks less than 1 mm. in length occurred at the gaps V and X, but not at the others, and although the same current was broken in the same way a great number of times, the phenomenon could not be reproduced. Fig. 28 shows the general form of the curve drawn by a current of 7,000 amperes maximum as it is broken by the circuit breaker. It shows that when the knife switches were closed the current rose so quickly that in $\frac{1}{1000}$ of a second it had reached 3,000 amperes, and in 0·008 of a second it had reached substantially its full value of 7,000 amperes. It remained almost constant for about $\frac{1}{25}$ of a second, and then as the circuit breaker opened it was gradually reduced to zero. The whole time from the closing of the knife switches to final breaking was only 0·14 second. The voltage curve V_b gives the pressure across the circuit breaker. This curve is on a very reduced scale. The zero of the volt line is displaced for the sake of clearness. There is, of course, no voltage across the breaker while it is closed, and the scale is too small to see any rise in voltage until just as the current dies to zero, when there is a rise which is roughly estimated at 300 volts.

The most interesting curves, however, were obtained when the rotary was short-circuited through 270 ft. of feeder cable, consisting

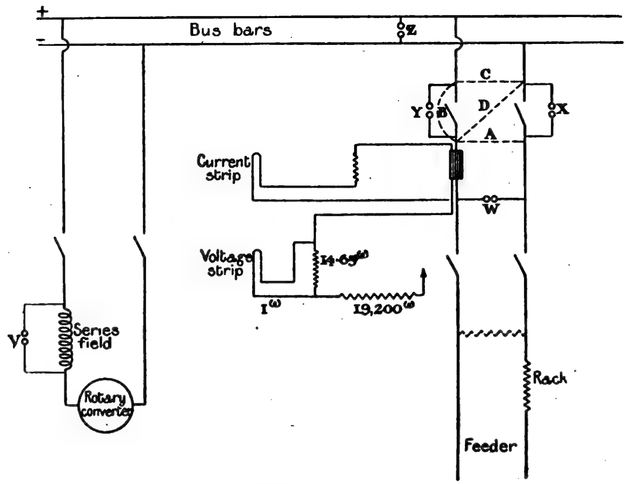


FIG. 27.—Diagram of Connections for Short-circuit Tests on Rotary Converters.

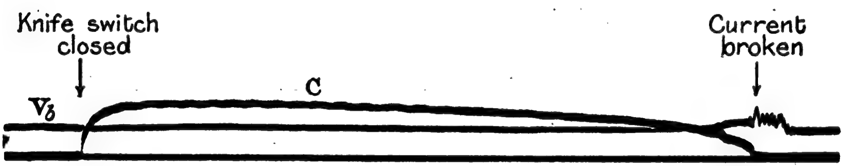


FIG. 28.—Oscillograph Record of Current in Line and Voltage across Breaker when an 800-k.w. Rotary is Short-circuited through a Low Resistance.

Current Scale ... 1 in. = 25,000 amperes.
Volts Scale ... 1 in. = 1,750 volts.
Time Scale ... 25 in. = 1 second.

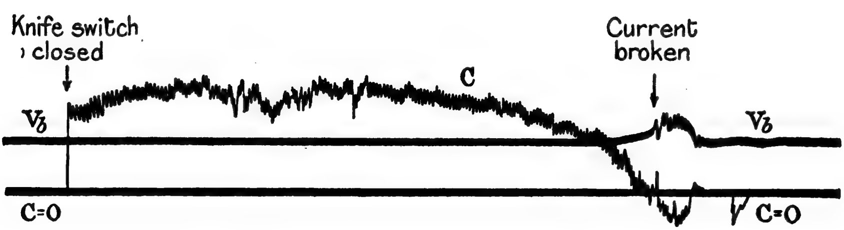


FIG. 29.—Oscillograph Record of Current in Line and Voltage across Breaker when an 800-k.w. Rotary is Short-circuited through a Short Length of Feeder.

Current Scale ... 1 in. = 25,000 amperes.
Volt Scale ... 1 in. = 1,750 volts.
Time Scale ... 25 in. = 1 second.

of 61/12s. S.W.G. wires. Fig. 29 is a diagram for this experiment; the maximum current reached was 14,000 amperes. As in Fig. 29, the current rises very suddenly; so quickly, in fact, that the spot of light has hardly made an impression on the photographic film. The small vibrations at the beginning of the curve correspond to the frequency of the slots in the rotary converter, and are probably caused by the sparking on the rotary, which would probably have a frequency corresponding in some measure to the frequency of the rotary slots. The way in which the current falls to 10,000 amperes after obtaining its maximum, and then rises again in jerks to 14,000 amperes, is rather remarkable. These fluctuations are probably due to commutating conditions controlling the length of arc on the commutator, in that way affecting the voltage. It will be seen that the current crosses zero and goes to a negative value, the maximum of which is beyond the margin of the film. It then crosses zero again and goes to a positive value of 250 amperes. It then goes negative again, forming an oscillation which has a frequency of about 0·0016 of a second. It then goes negative and after certain fluctuations falls to zero.

This oscillation of the arc is extremely interesting, and it is conceivable that with certain values of self-induction and capacity in the circuit, combined with the blowing-out action of the air arc which Steinmetz has described, it might give rise to very high rises of pressure on the circuit breaker.

It will be seen, however, from curve V_b that the voltage rise on the circuit breaker is not more than 500 volts. There is, however, an oscillation of voltage which is exactly timed with the oscillation of the current.

Although the rotary was short-circuited on this short feeder a number of times in succession, the spark-gaps were not broken down. If these experiments are reproduced again, means will be provided of changing the self-induction and capacity in series with the rotary.

The experiments show that unless these quantities have such a value as to give to the circuit a natural period of vibration which is in some way related to the peculiar operation of the arc, no serious rise of pressure occurs, even when a very large current is broken.

It has been thought that the bringing of these matters before the Institution might lead to a fruitful discussion.

I wish to acknowledge my indebtedness to the many firms who have kindly sent me photographs and descriptions of their armature windings.

THE DESIGN OF TURBO FIELD MAGNETS FOR ALTERNATE-CURRENT GENERATORS WITH SPECIAL REFERENCE TO LARGE UNITS AT HIGH SPEEDS.

By MILES WALKER, Member.

(*Paper received November* 10, 1909, *and read in London on March* 10, 1910.)

SUMMARY.

This paper re-opens the controversy between the salient pole type of field magnet and the cylindrical type. Reasons are given why the latter type is better suited for obtaining the greatest possible output from a given diameter. The methods adopted by various makers of supporting the windings are described, and the possible limits of output considered.

THE NECESSITY OF PROVIDING LARGE GENERATING UNITS OF HIGH SPEED.

In the discussion which followed the paper by Dr. Kloss, "Practical Considerations in the Selection of Turbo Alternators," before the Manchester Section of the Institution of Electrical Engineers in November, 1908, an argument arose as to whether the field magnets of turbo-generators should be made with salient poles or should be of the cylindrical type with a distributed winding. Some difference of opinion exists among designers on this point, and each method has been adopted in quite a large number of successful turbo-generators. In the opinion of the author the matter is one of great importance, because, in the future, makers of turbo-generators will be called upon to build machines of larger capacity than ever before contemplated, and the makers of steam turbines to drive them will call for extremely high speeds, so that the turbo-generator of the future will have to be capable of giving an extremely large output from a diameter which is not excessive, and will have to be constructed in a manner which permits of a high factor of safety.

If we look at the growth in the kilowatt capacity of machines during the last thirty years, we are driven to the conclusion that the kilowatt capacity of large units in the immediate future will be as great as 15,000 or 20,000 k.w. In the year 1880 a 10-k.w. machine was considered large; in 1885 a 100 k.w.; in 1890 a 300 k.w.; in 1895 a 500 k.w.; in 1900 a 1,000 k.w.; in 1905 a 5,000 k.w.; in 1910 we have

10,000-k.w. steam turbine-driven generators and 17,000-k.v.a. water turbine-driven generators.

The cheapening of the cost of generation of electricity and the reduction in the capital required per kilowatt installed are already being felt in the widening of the field in which electricity is being used, so that in the near future we may expect the output of electricity stations in all our large towns and manufacturing districts to be enormously increased, and the great requisite will be large generating stations at low capital cost. For capital cost is one of the main items which go to make up the price at which electricity can be supplied. These large units will in many cases consist of impulse turbines of very high speed and very large capacity.

The Salient Pole Type *versus* the Cylindrical Type of Field Magnet.

The author has therefore thought it would be well to open again the discussion upon the salient pole type and the cylindrical type of

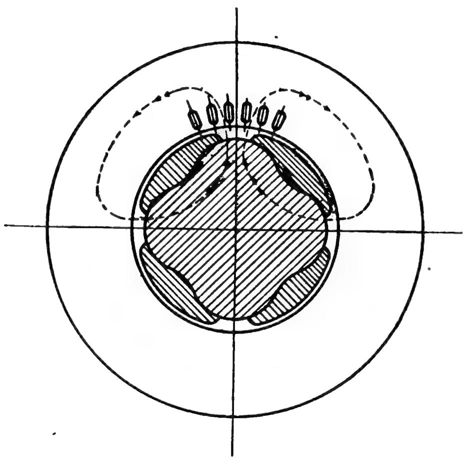


Fig. 1.

field magnet, and to consider the advantages and disadvantages of each of these types, with special reference to machines of very large output and very high speed.

Let us consider first the essential features of a field magnet and the duties which it has to perform. We will take for granted that the field magnet is the rotating element, because it is difficult to support satisfactorily a rotating armature winding wound for a high voltage, and it is not desirable to collect current generated at 6,000, or 11,000 volts from slip-rings.

Fig. 1 shows a section through the iron parts of a stationary arma-

ture with the winding turbo-alternator. The duty of the field magnet, which we will take as having four poles, is to produce a magnetic flux which crosses the gap in a radial direction, and returns through the iron of the armature back to the core of the magnet. To produce this flux, we shall require a winding placed so that it produces a magneto-motive force in the direction indicated by the arrows in Fig. 1.

The Two Factors in the Output.—The output of a field magnet is proportional to the product of two factors:—

1. The cross-section of the iron of the path indicated by the arrows (Fig. 1).
2. The ampere-turns carried by the copper winding.

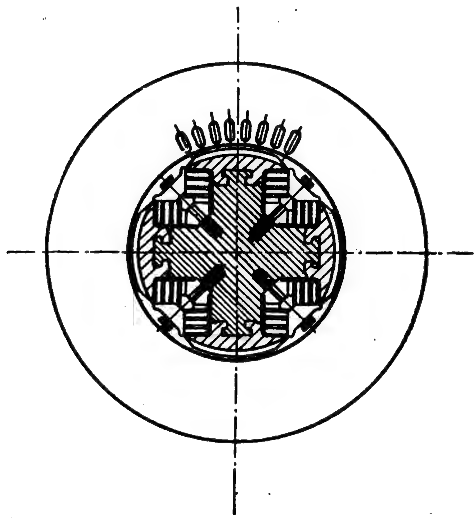


Fig. 2.

The cross-section of the path would be largest if the rotor consisted of a solid cylinder of iron filling the whole space, in which case there would, of course, be no room for the copper. The ampere-turns would be greatest if the whole space were filled with a copper winding, in which case there would be no iron for the flux. The best theoretical arrangement would be a disposition of copper and iron something like that shown in Fig. 1, in which the iron and copper are put in those places where they are most useful, and least interfere with the presence of one another. Such an ideal disposition of iron and copper would, of course, be difficult to carry out in commercial manufacture, but the type of rotor which most nearly approximates to this, will be the one which will give the greatest output in the smallest space.

One of the main considerations which determines the arrangement

of iron and copper on a turbo-rotor is the necessity of supporting the parts against the great centrifugal forces.

The Salient Pole Construction.—The salient pole at first sight appears to offer very great facilities for supporting the copper winding, because it can be made with a projecting lip all round the pole. Fig. 2 shows the field magnet of one of the 4-pole turbo-generators lately described before this Institution.* This is mechanically a very good construction.

In cases where it is decided to go to extremely high peripheral speeds, and additional support is required for the independent coils, the type shown in Fig. 3 may be employed. Here the coil on each

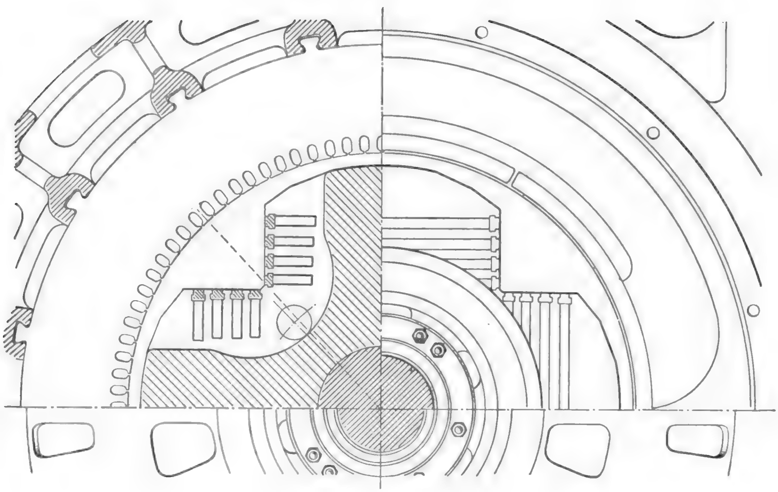


FIG. 3.

pole consists of four parts wound in slots cut out of a solid steel forging. Or if it is desired to construct the pole of laminations, the type shown in Fig. 4 may be employed, and great mechanical strength at the same time obtained. Very successful turbo-generators have been built according to the methods illustrated in Fig. 2, 3, and 4.

It will be observed, however, from these figures that there is between all the poles a space which is not utilised at all, and that is the very space where the copper winding should be, according to the ideal arrangement in Fig. 1. This space can be utilised to a certain extent for the purpose of ventilation It is, however, frequently occupied by bronze coil supports which are found necessary to prevent side bulging of the coils.

With the coils placed as shown in Figs. 2, 3, and 4, the cross-section

* G. Stoney and A. A. Law: "High-speed Electrical Machinery," *Journal of the Institution of Electrical Engineers*, vol 41, p. 300, 1908.

of the pole is necessarily reduced, and therefore one of the factors of output (No. 1 above) is reduced. It will be seen that the reduction of the total flux of a generator reduces its output in a way that can never be quite compensated for by increasing the ampere-turns, because the capacity of the armature is in any case limited to a definite number of ampere-wires per inch of periphery on account of heating considerations, whereas the flux-carrying capacity of the armature iron can be extended by increasing the outside diameter of the punchings.

A type of field magnet which very effectually gets away from the necessity of side supports for the coils is that shown in Fig. 5, where each pole consists of a number of round poles placed side by side on a central boss. This construction, however, has the drawback of still

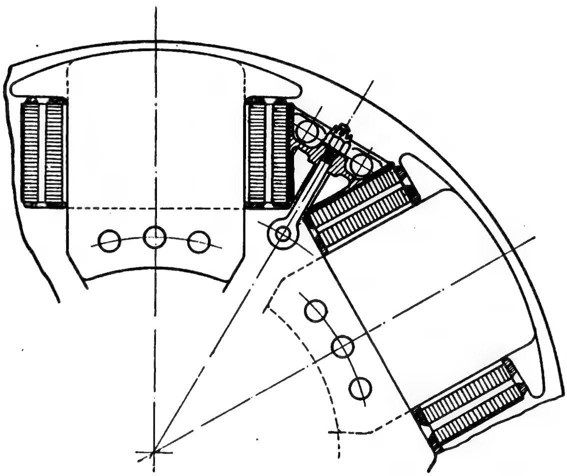


FIG. 4.

further reducing the cross-section of the iron path, but it leaves a large amount of space available for ventilation.

With the salient pole type the ends of the coils are easily supported by a projection from the ends of the poles. The coils, moreover, are comparatively simple in form and cheap to construct, and the length of mean turn is not great for a given cross-section of iron enclosed. The coils can be easily replaced.

The Cylindrical Type Construction.—The advantage of the cylindrical type with distributed winding, as illustrated in Figs. 6 to 15, is that by placing the winding in slots between iron teeth we can utilise a great part of the periphery both for carrying flux and for carrying ampere-turns. In order to obtain a generator of good regulation, it is necessary to have the ampere-turns at no load upon the field magnet greater than the ampere-turns on the armature. Where the iron body of the pole and the iron core of the armature offer very little magnetic

reluctance, it is necessary to introduce into the magnetic circuit some part, such as a large air-gap, which will offer a large reluctance, and enable the ampere-turns on the field magnet at no load to be of the required amount. It is therefore seen that the interference with the magnetic circuit caused by the slots in Fig. 6 is rather beneficial than otherwise, for the flux path being constricted in these teeth, there is a drop in magnetic potential just as there is in an air-gap. The teeth and slots may therefore be taken to replace in some measure a large air-gap; in fact, saturated teeth employed in this manner give an even better characteristic than an air-gap, as is shown in connection with Fig. 20 below. Again, the space taken up by the teeth does not seriously interfere with the space required for the copper, because the iron presents a large surface to which heat can be conducted from the copper, and in that way enables the copper to be worked at a higher current density than otherwise would be the case.

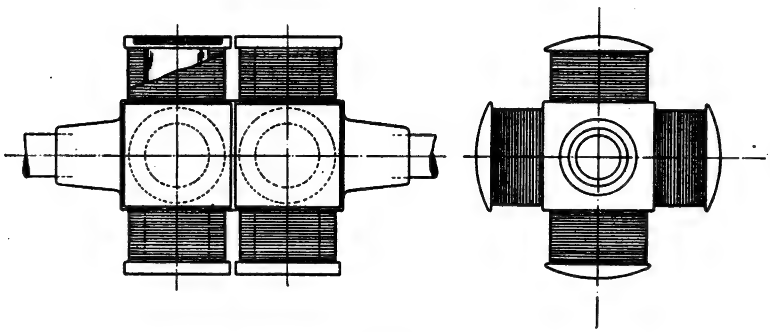


FIG. 5.

Thus we see that with the arrangement shown in Figs. 7 to 12 the iron and copper, though each, to a certain extent, encroaches upon the space required for the other, mutually assist one another. It will be seen, too, in Fig. 6, that the iron below the slots offers such a large cross-section for the flux path that we can easily spare space for a number of large holes which traverse the field magnet from one end to the other, and supply air to a number of radial air ducts. Thus with the cylindrical field magnet we obtain a very large cooling surface on the insulation of the copper winding by which the heat can be carried from the copper to the iron, and also very large surface within the ventilating ducts, by which the heat can be carried from the iron to the air.

It is found in practice that copper placed in such slots can carry twice as many ampere-turns per square inch as copper in a wound coil $2\frac{1}{2}$ in. in thickness. There is a distinct advantage in supporting comparatively small sections of copper winding in independent slots, because by so doing one can preserve a high factor of safety in the

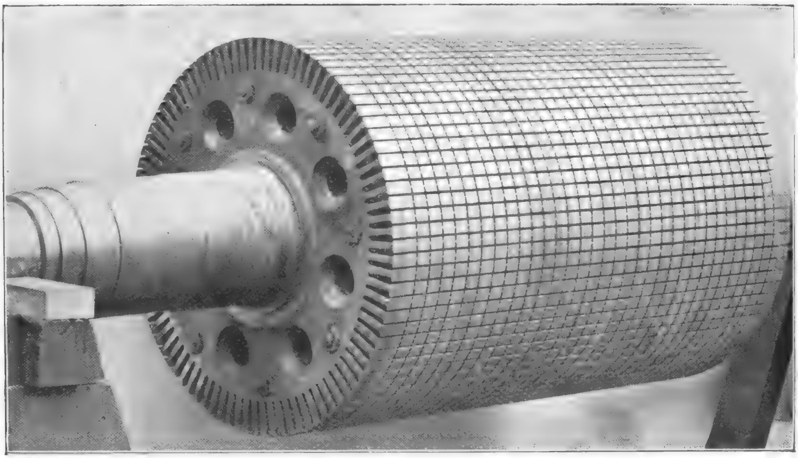


FIG. 6.

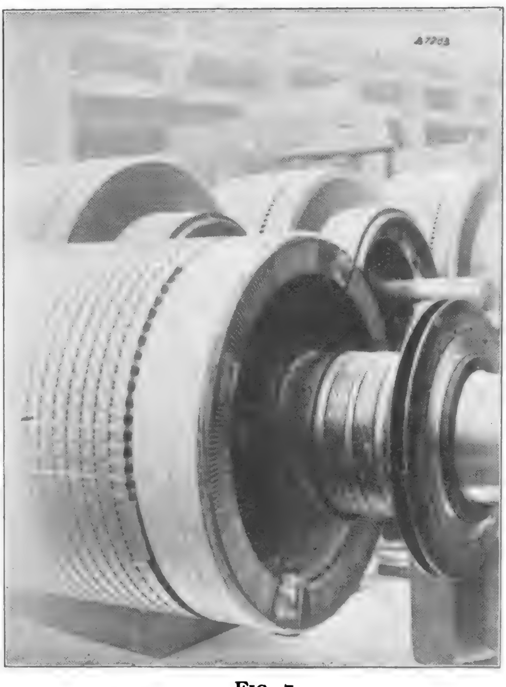


FIG. 7.

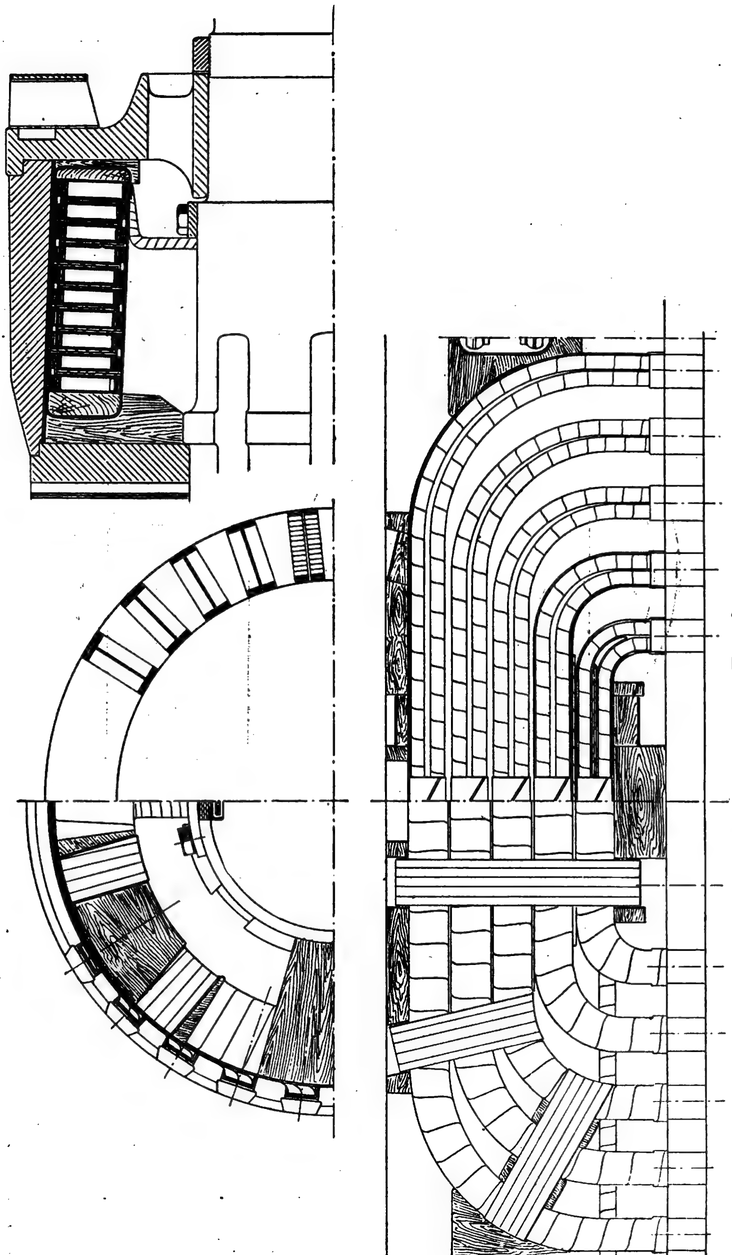


Fig. 8.

pressures thrown on the insulating materials, and by avoiding a great number of successive layers of insulation one is able to avoid troubles due to shrinkage of the insulating material.

A drawback to be set off against this is that the length of mean turn for a given area of iron enclosed is greater than in the salient pole construction.

Methods of Supporting the End Connections.—The main difficulty with the early cylindrical field magnets having windings distributed in slots was the supporting and cooling of the connections from one slot to another at each end of the rotor. Various methods have been adopted for making these end connections. One type is illustrated in Fig. 7 in which the connections form a barrel winding, similar to that used on direct-current armatures. This type has the following advantages:

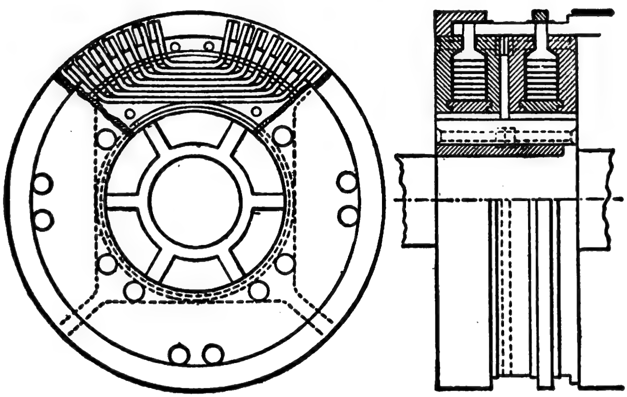


FIG. 9.

All the conductors are made of the same shape, and the connections between them are very easily made by means of thimbles placed over the ends. The insulation of the winding can be carried out very effectually, and when well constructed and secured by wire or solid metal rings placed over the end connections, it preserves its balance extremely well.

Another type is shown in Fig. 8. This consists of concentric coils and is perhaps the best type of winding to employ where the exciting current is small (say 50 to 100 amperes supplied at a high voltage), and where, therefore, a great number of comparatively small conductors must be placed in each slot. This winding may be supported by a metal ring placed over the ends, as shown in Fig. 8, or by means of a sheath strengthened by numerous rivets or bolts.

Another method of supporting the end connections is shown diagrammatically in Fig. 9. Here the end connections consist of copper straps bent into the required shape, insulated from one another, and assembled so as to form a solid fan-shaped block. Four of these

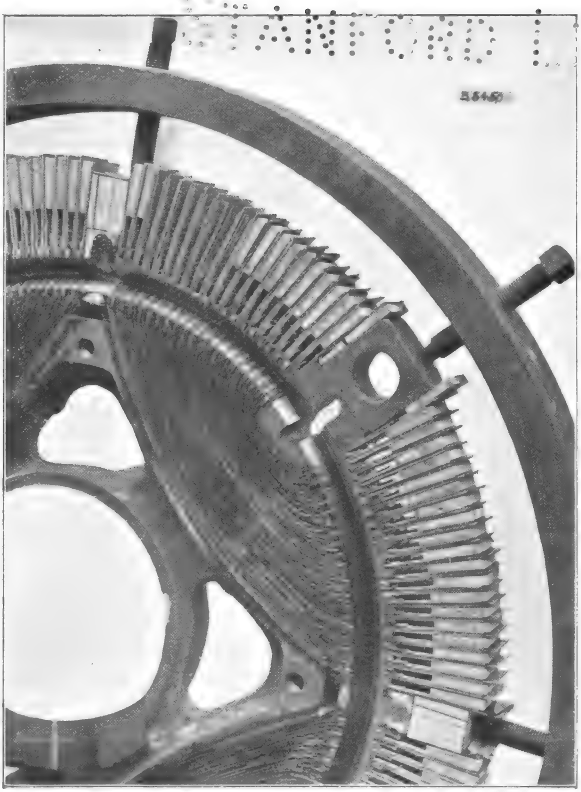


FIG. 10.

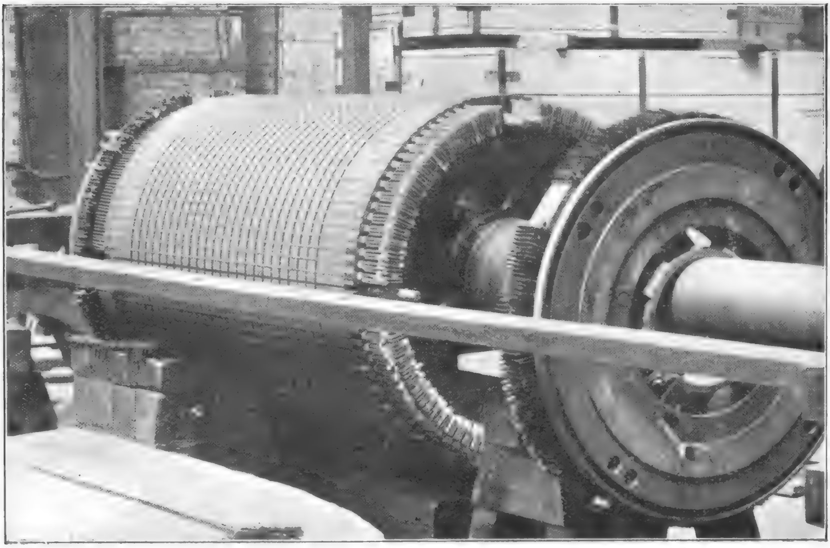


FIG. 11.

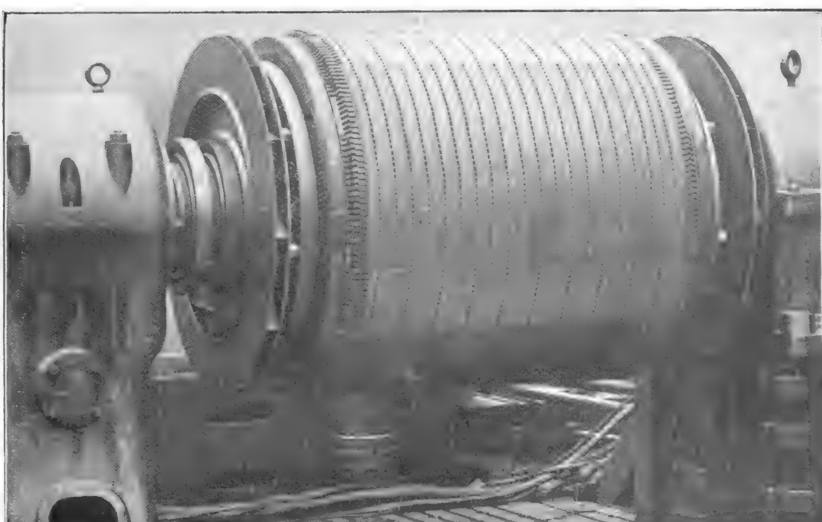


FIG. 12.

blocks are mounted on a saddle and V-shaped grooves are cut as shown in Fig. 10. The whole is then assembled between steel cheeks having V-shaped protections, mica V-rings being placed in the grooves, just as in the construction of a direct-current commutator. Fig. 11 shows the assembled end connectors being pressed on to a field magnet on which the field bars have already been placed in the slots. Fig. 12 shows a field magnet completed. A great number of field magnets have been constructed in this manner on machines intended for very high peripheral speeds, and they have proved very satisfactory both mechanically and electrically.

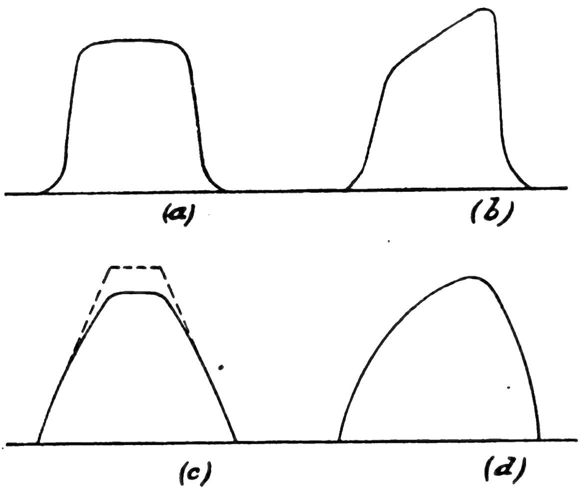


FIG. 13.

The important points to be aimed at in the designing of the winding of turbo-generator field magnets are as follows :—

1. Although the field magnet is excited at a comparatively low voltage—125 or 240 volts—the insulation must be carried out with the very greatest care. It is found that the dust which settles on the revolving parts of turbo-generators can, under certain circumstances, be so highly compressed by centrifugal forces that it becomes a much better conductor than the dust found on slow-speed machines. Cases have been experienced where pressures as low as 50 volts have caused the current to leak over considerable distances of dirty insulation.
2. The insulation should be of such a nature that it does not permit the conductors to move in a radial direction after it has become dry.

3. Allowance must be made for expansion and contraction of the copper.
4. Provision must be made for the cooling of the end connectors.
5. The design should be such that a repair of one part of the winding can be carried out with as little disturbance as possible of the remainder of the winding.

Field Form.—The flux distribution on no load on the face of the armature of a salient pole machine is shown in Fig. 13A. At full load the field becomes distorted as shown in Fig. 13B, and if the armature is constructed with open slots, there is a tendency for the peak in the wave of the field form to produce ripples in the E.M.F. wave-form. These ripples, though of little consequence in the operation of most alternating-current machinery, may give rise to dangerous voltages

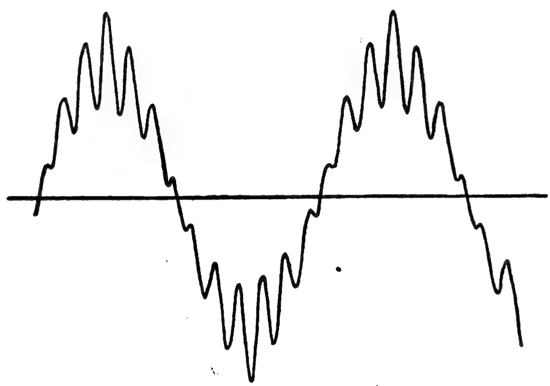


FIG. 14.

when the generator is feeding a large system of cables, whose capacity happens to give to the system a natural period of vibration corresponding, or nearly corresponding, with the frequency of the ripples. For this reason armatures provided with open slots are not as good as armatures with semi-enclosed slots unless the number of slots per pole is very great, the air-gap very long, or the field-form entirely free from peaks, such as shown in Fig. 13A. Ripples which on a no-load wave-form are scarcely perceptible may, when the capacity of the circuit assumes a certain critical value, be exaggerated, so that the E.M.F. wave-form assumes a shape like that illustrated in Fig. 14. In this case the crest-factor * may be very greatly augmented and a serious pressure thrown on the cables. An E.M.F. wave-form closely resembling a sine wave-form and free from ripples both at no load and on full load is of considerable commercial importance.

* "Crest-factor" is a term proposed by Dr. Gisbert Kapp for the ratio between the maximum value and the square root of mean square value. In the original paper the author used the term "form-factor."

Let us take an example: When a designer of a distribution system is deciding upon the voltage which he shall adopt for his high-tension transmission, he considers all the risks of breakdowns to his cables and apparatus, and chooses that particular voltage which in his mind is the most suitable for his requirements. If he choose a higher voltage he will save copper; if he choose a lower voltage, he will make his insulation safer. Now suppose that he fixes upon 6,600 volts, and then buys a generator which has a crest-factor under certain conditions of load of 1·9. With a crest-factor of 1·9 on a virtual voltage of 6,600, the maximum voltage on his cables will be 12,500. This is the voltage which the insulation has to stand. If he had bought a generator with a true sine wave-form, whose crest-factor is only 1·41, he could with equal safety—so far as insulation is concerned—have employed a virtual voltage of 8,900. In so doing he would have saved 50 per cent. of the copper in the mains.

The field-form of the cylindrical type of field magnet with a distributed winding is shown in Fig. 13C. The dotted line shows the distribution of magneto-motive force along the air-gap. The full line shows the form taken by the field. It will be seen that owing to the saturation of the teeth near the centre of the pole the corner of the field-form is nicely rounded off. Fig 13D shows the full-load field-form. Here again we have a nicely rounded curve free from elevated peaks. In order to arrive at the wave-form of E.M.F. yielded by a generator of this type of field, it is necessary to take a number of these field-forms, corresponding to the number of slots in 2 phase-bands of a 3-phase armature, displaced from one another by the amount of difference in phase between the various slots and to make a summation of them all. This yields an E.M.F. wave-form so nearly approximating to a sine wave as to be hardly distinguishable from it at no load, and at full load it only suffers a slight distortion.

Voltage Regulation.—In order to make an ordinary alternate-current generator regulate well, it is necessary to have a large ratio between the ampere-turns on the field and the ampere-turns on the armature. With turbo-generators it is not usual to have this ratio greater than 2; in many turbo-machines it is considerably less. In these cases it is usual to saturate the field magnet to a fairly high point, so that when the load is thrown off the extra ampere-turns in the exciting coils which were necessary to keep up the voltage on load shall not be able to create too great a rise in voltage. There is considerable danger in employing a very highly saturated field magnet, because it is always difficult to be sure of the quality of iron, and if the saturation is carried too far, it may be found impossible to obtain the voltage of the machine on heavy loads at a low power factor.

It is important in this connection to consider at what part of the pole the saturation occurs. If the generator is of the salient pole construction and the saturation occurs at the root of the pole, there is much more danger of being unable to obtain full voltage than if the saturation occurs in teeth distributed near the periphery field of the

magnet. The reason of this is that the leakage is greater with the salient pole than with the cylindrical type. The leakage flux from the pole combines with the working flux in producing the saturation, and as the leakage flux is almost proportional to the ampere-turns on the pole, we increase the leakage and consequently the saturation at the same time that we increase the field current.

Fig. 15 shows the shape of the saturation curve of a machine with salient poles both at no load and at full load, where the saturation has been designed to be rather excessive. It will be seen that at heavy load on a low power factor the saturation curve is almost asymptotic to a horizontal line, so that though the field current may be raised to very high values, the voltage cannot be increased beyond a certain

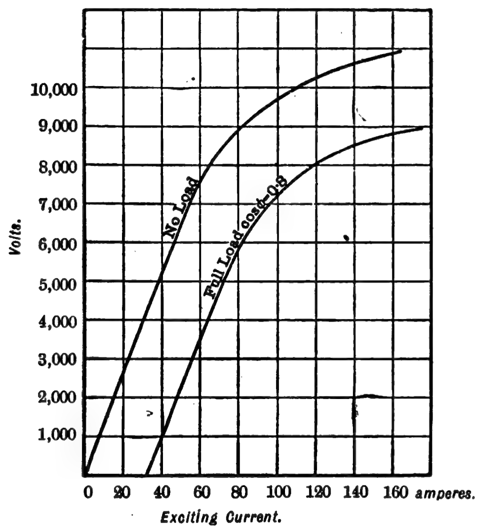


FIG. 15.—Salient Pole Saturation Curves.

point. Fig. 16 shows the shape of the saturation curve of a generator with a cylindrical field with highly saturated teeth both at no load and on a low power factor load. Here the curve never becomes asymptotic to a horizontal line, because at the worst the space occupied by the copper and teeth will operate as a long air-gap, and there is no saturation in the body of the pole.

An important advantage of the cylindrical type field magnet is that it is easy to arrange it so as to embody the compensating principle described on a previous occasion,* and make the armature reaction strengthen the field. This enables good regulation guarantees to be made without necessitating a very great ratio between the ampere-turns on the field and the ampere-turns on the armature. With this

* *Journal of the Institution of Electrical Engineers*, vol. 34, p. 402, 1905.

type of machine it is possible to get good regulation (2 per cent. at unity power factor and 12 per cent. at 0·8 power factor) even with the ampere-wires per inch of periphery as high as 1,000. It is also possible to employ a flux density in the air-gap as high as 11 Kapp lines per square inch. From these two quantities it is easy to calculate the possible output of a 4-pole generator running at 1,500 revs. per minute. Suppose that we decide not to go to a greater diameter than 44 in., or to a greater length than 70 in., though these figures could be increased by adopting special construction.

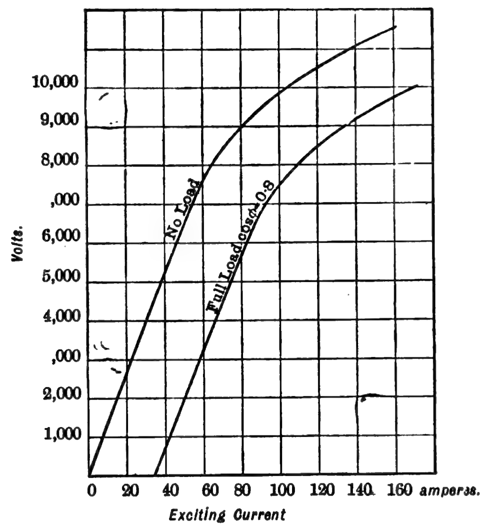


FIG. 16.—Cylindrical Field Saturation Curves.

The possible output is easily calculated from the following considerations :—

Let—

B_K = maximum Kapp-lines per square inch in the air-gap.
P = the periphery of the rotor in inches.
l = the length of the rotor in inches.
W = total conductors in all three phases.
A = the amperes per phase in a 3-phase generator.

Then—

$$\text{Volts} = 0{\cdot}4 \times \text{revs. per minute} \times W \times B_K \times P \times l \times 10^{-6}.$$

$$\text{Output in kilovolt-amperes} = \text{amperes} \times \text{volts} \times 1{\cdot}73$$
$$= 0{\cdot}69 \times \text{revs. per minute} \times A \times W \times B_K \times P \times l \times 10^{-6}.$$

Taking $A \times W$ at $1{,}000 \times P$ and B_K at 11, we get—

$$\text{Output} = 0{\cdot}69 \times 1{,}500 \times 1{,}000 \times 140 \times 11 \times 140 \times 70 \times 10^{-6}$$
$$= 15{,}500 \text{ k.v.a.}$$

By adopting special ventilating arrangements which will permit the bearings to be brought near to the ends of the rotor iron, the length of the rotor can be increased beyond 70 in. without giving the critical speed an unsuitable value. Then the output can be increased in proportion. Again, if we are content to have a poorer regulation we can increase the ampere-wires per inch of periphery considerably beyond 1,000, and in that way still further increase the output.

In the above I have considered only the 4-pole machine. The outlet of a 2-pole generator is very much smaller, because the iron in the body of the pole becomes saturated long before the density in the air-gap reaches 11 Kapp-lines per square inch, and the ampere-turns cannot be made as great. With a 4-pole field it is possible to work as high as 11 Kapp-lines without incurring any trouble from unbalanced pull, because with the compensated type of generator the density in the gap is almost independent of the length of the air-gap. The rotor illustrated in Fig. 12 is for a 4,000-k.w. generator built for the Glasgow Corporation. It holds its voltage constant within 2 per cent. from no load to full load at 0·93 power factor. In this machine the density in the air-gap is 11 Kapp-lines, and by actual trial it was found that there was no serious unbalanced magnetic pull with a radial displacement of $\frac{1}{16}$th in. An important feature of this type of rotor is that while it gives good inherent regulation at ordinary power factors, the armature current on short circuit can be made quite small—that is, 1·5 times full-load current for the permanent value and about 10 times full-load current for the instantaneous value. The low value of this current is of importance when we have to design the windings to withstand the forces to which they are subjected at the instant of short circuit.

Discussion.

Mr. Chamen.

Mr. W. A. Chamen: Personally I am more than usually interested in these papers, because I have a 3,000-k.w. alternator designed by the author, and although we have had one or two short circuits, and have been rather alarmed at the noise and dust from the alternator when short circuits occurred on the distribution system, making one think that it is smoking, we have never had a breakdown. I think that speaks volumes, particularly when I tell you that it is very probably the first 2-pole alternator of 3,000-k.w. capacity running at 1,500 revs. per minute. There are plenty of 4-pole machines, but I have not been able to find any 2-pole machines of that size. As the author says, the strains in a 2-pole machine are very much greater, and the strains in our case certainly were very remarkable. We knew before the alternator was put in that we should have these strains to deal with, and I therefore took some trouble to look into the question of the clampings and fixings employed, and I am bound to say that I did not think anything could happen even if we did have a short circuit. As a matter of fact, the big inch studs holding the clamps have been bent in various directions and the coils themselves have been pushed out of

Mr. Chamen.

place, but no breakage of the insulation or anything of that kind has occurred. Of course, we feel that something further is required, and after the careful investigations the author has made, I feel quite sure that he will succeed in putting our alternator into such a condition that even these movements cannot take place. There was one point at the end of the first paper that interested me greatly, dealing with direct currents. It is very interesting to read of these cases of leaping cables. It carries one back to what happened with underground mains some years ago in the days of copper strip. I recollect one case in Glasgow, where a bad short circuit occurred on some copper strips laid on supports about a yard apart. The strips were each about 1-in. wide and ¼-in. thick. A heavy short circuit occurred, resulting in their being festooned outwards all along the street. We had to take them all out. The cables coming from Glasgow Corporation main generating stations were laid in iron troughs fixed on a kind of bracket frame, with no clamping at all. These were big cables with 1 sq. in. conductors, and although there were occasional short circuits, there was never any case of movement. I suppose the reason is that the cables were concentric. The surging effect on breaking a continuous current I have never investigated, but I am well aware that it exists. In Glasgow I had a case where in starting up a 3-wire generating station the two dynamos were accidentally run up in such a way that the 3-wire system instead of working in the proper way was working with the middle wire as a common return for the two others. Not wishing to stop the supply, I had arranged that late at night, when the load had gone down considerably, the wrong side of the system was to be suddenly switched out and then reversed by switching on to the battery. At the instant of performing the operation one of the cables broke down. There was no reason why it should have broken down except from a surge. It was afterwards found that there was a constructive fault causing a weak place in the cable, which was the place where the actual breakdown occurred. I think that is exactly a case in point like that mentioned by the author.

Professor Silvanus Thompson.

Professor SILVANUS P. THOMPSON: There are not very many electrical engineers who would be able to speak on these subjects with the authority and power with which the author speaks, for the very good reason that there are not very many electrical engineers in the world who, in the first place, have the opportunity of designing large turbo-alternators and turbo-generators in the works under their control, where they can try experiments on short-circuiting them; and who, in the second place, if they have the opportunity of designing, testing, and experimenting with machines on such an enormous scale, have the ability and the permission to publish the result of their labours. These papers, like the one that was recently read by Mr. Hope-Jones before this Institution, show us what a valuable tool of research in every branch of electrical engineering the oscillograph has proved itself to be. Thanks once more to the oscillograph, we know a great deal more of what happens at a big short circuit than we knew before,

Professor Silvanus Thompson.

and knowing what happens we have the best means for preventing accidents caused by such short-circuiting. The arguments in the first paper about the surprising amount of the rise of current at the moment of short circuit take some of us, I have no doubt, back to the troubles there were years ago in central stations using alternating generators. These were of much smaller sizes than at present, and yet a short circuit, if it did occur, was a most terrible thing because it upset the whole station. I remember perfectly well years ago discussing in the old station of the City of London Electric Light Company the effect of the breakdown of some of Mr. Mordey's early form of alternators, which then were the last new thing; and I expressed the opinion—as the result of the effects of the distortion of the conductors—that the short-circuit current had been twenty to thirty times as great as the ordinary full-load current. That opinion, purely based on the mechanics of the thing, was hotly disputed at the time, not so much by Mr. Mordey himself as by Mr. Raworth, who stoutly maintained that the short-circuiting current of these machines was only two or three times their normal full load. They had tried it; they had short-circuited their machines when these were running round unexcited, and then gradually increased the excitation until the excitation was equal to the normal excitation, and the short-circuiting current under those conditions was only two or three times the ordinary full-load current. I admitted it was so probably in their experiments, but I still maintained, without any other evidence, that it must have been very much greater—that it was twenty or thirty times. I do not say they laughed at my opinion, but my opinion was certainly discounted. I was never able quite satisfactorily in my own mind to explain the discrepancy until I saw the author's paper on the subject, but it is now evident that the demagnetising effect of the short-circuit current has not time to come into play during the first moments of short-circuit, and therefore, because the field magnets have not time to become demagnetised, the short-circuit current is, as he says, twenty, thirty, or more times as great as the ordinary full-load current. The discrepancy is now quite cleared up. Another matter of some interest is the reaction which occurs in alternators with laminated field magnets, where, as there is no eddy current in the polar masses to take up the burden of the reaction, the reaction pumps itself into the exciting circuit, and the exciting coil does its best to recover the situation, and grows to double value at the first moment. At the beginning of the second paper the author told us—and we smiled at the beauty of it—that the proper thing in the first place was to fill the entire space of the rotor with iron, and secondly to fill the entire space with copper; that each required as much space as it could get. Then he gave us a picture of an unrealisable ideal, a 4-pole rotor with the copper in the right place, but impossible from the mechanical point of view. It rather reminded me of something that was said years ago about the use of field magnet windings. The use of field magnet windings was to drive the magnetic flux across the air-gap;

obviously therefore the exciting coils ought to be wound round the air-gap and not round the iron. Mr. Eickemeyer tried to do it, and he was quite right theoretically; but purely mechanical considerations made it difficult to realise the ideal. But now the author has shown us how much nearer we are getting to the ideal if we adopt the embedding of the exciting coils in peripheral slots instead of winding them round discrete salient poles. Professor Silvanus Thompson.

Here I am going to quarrel for the first time with the author, but only over a very small point. He has been talking to us about the "output" of a field-magnet. I do not want words used in two meanings. I thought "output" was always a question of kilowatts, but the author does not mean that at all. He means the biggest effect that can be got out of a field-magnet, proportional therefore to its magnetism, the flux, and to the ampere-turns that drive that flux. I think we ought to call that the "duty" of the field-magnet and not its "output." The duty of a field-magnet is not only to provide a flux but to provide that flux with a sufficient magnetomotive power behind it to hold it up against the reactions. If we translate that into dimensions, or, as the author says, into area, we shall require for the flux a certain area of iron and for the ampere-turns a certain cross-sectional area of copper. The area of the iron is proportional, other things being equal, to the diameter and to the length of the rotor; the cross-section of the copper, other things being equal, of similar construction, is proportional to the square of the diameter and independent of the length. If we multiply those two factors together to get the duty of the rotor, the duty of the rotor is proportional to the cube of the diameter and to the length, which shows us that it is much more important if we want to get a good duty out of a quantity of material to increase the diameter than to increase the length. By increasing the diameter the effect goes up in proportion to the cube of the increase; by increasing the length it is proportional simply to the increase. If the length be increased by 5 per cent. the duty of the rotor is increased 5 per cent.; but if the diameter be increased by 5 per cent. the duty of the rotor is increased by 15 per cent. That is not unimportant, I think, in connection with the designs for large machines.

The author spoke about the compensated winding which he described to us in a paper* the importance of which I think the world has not yet really understood. I would ask him to describe his method of adapting this plan of embedding in slots to the production of his compensated winding which has so many virtues. It is no small gain, I think—at least if we take these figures as being partly the result of the compensated field magnet winding—to be able to increase the specific load of the armature in the way in which the author has been enabled to do. One is accustomed in ordinary constructions to say that the top limit for the specific loading of an armature is somewhere of the order of 600, or possibly 650 ampere-wires per inch of periphery;

* *Journal of the Institution of Electrical Engineers*, vol. 34, p. 402, 1905.

Professor Silvanus Thompson.

but now we go all of a sudden up to 1,000, and even that is not the limit to which we may go. We may have 1,000 ampere-conductors per inch of periphery, and yet not have such an amount of distortion or demagnetisation as to make a machine a bad-regulating one, even when the ampere-turns per pole of the field magnet are not more than one and a half times the ampere-turns per pole of the armature at full load. That is a very remarkable result; and if this great gain in the magnitude of the specific loading is due to the use of the particular form of rotor that he suggests or prefers, and to the compensated winding, it marks a real advance. Anything that enables us to use that bigger specific loading clearly adds to the output in proportion to the size, and brings down the prime cost of construction. The author put emphasis quite rightly upon the advantage of not having ripples in the electromotive force curve. He remarks that ripples are a matter of commercial importance. But why should there be any ripples? If a field magnet be built up with a nearly smooth peripheral outline, and with several slots per pole per phase, I do not see that there need be any ripples, provided advantage be taken of a thing that is perfectly well known; that even comparatively strongly marked ripples can be smoothed out by the mere device of not having the slots in the armature exactly parallel to those in the rotor; one or other of them may be slightly skewed round. I know that this will add to the difficulties of production, but in smaller machines it is a common thing to have the slots not exactly parallel to the axis but set askew, and this will cure all the ripple troubles if there are any.

There is one other little point of criticism which I must mention. I do not like to hear the term "form factor" used for something else than that which we all know as form factor. The form factor of an alternating wave as given in all the text-books is the ratio between the square-root-of-mean-square value, and the average value. For a sine curve the form factor is the ratio of 0·707 to 0·637, or about 1·1; but we had the term "form factor" used to-night in an entirely different sense as the ratio between the peak value and the root-mean-square value, what Arnold calls the "Scheitel-faktor," the thing on which depends, not the virtual electromotive force, but the piercing value, the value which tends to break down the insulation. The author should not call it the "form factor" when that term is already used for something else.

Mr. Hobart.

Mr. H. M. Hobart: The author states on page 304 of his paper that in one machine which he tested the magnet cores were solid, and that in that case the current in the exciting circuit, instead of rising from the instant of the sudden short circuit, decreased at first, but in the case of a machine with laminated magnet cores, the current increased in the exciting circuit from the moment of short-circuiting. Some years ago I tested six 5,000-k.w. machines at a Continental works for this sudden short-circuit effect. In that case, the pole-shoes were laminated but the magnet cores were solid, and the current in the exciting circuit increased from the instant of short circuit. The machines were in some ways very different from those dealt with by

Mr. Hobart.

the author, because they were not for such high speed. They were 5,000-k.w., 300 revs. per minute 20-pole machines, so that the forces that came into play could be much more readily dealt with by reasonable mechanical construction, than in the case of 4- and 2-pole machines of the same capacity, but for steam-turbine speeds. Nevertheless, the machines were exceedingly interesting, and I call attention to this point of difference because it may lead to some useful comment from those present as to why, in the case of my machine, the current rose, and in the case of the author's machines with solid magnet cores, it fell. In my machine the current in the exciting circuit rose rapidly to something like two or three times the normal value at which it had been adjusted previously to short-circuiting the armature, and it suggested to me that the whole phenomenon might be modified with advantage to the machine, by putting in the field a cut-out, which should operate when the current had risen to a value some 50 per cent. greater than the normal exciting current. I suggested that at the time, but it was never acted upon. These machines were not, as I have pointed out, very extreme. Most of the disastrous occurrences have taken place within the last few years, and I find that there is a general impression that the phenomenon has not been known for very many years. As a matter of fact, it was unknown to me prior to taking this work in hand six years ago. My instructions were to test the machines for the sudden short-circuit phenomenon, and that was the first time my attention was drawn to the matter. It is interesting to note that at that comparatively early date (probably others will mention earlier dates in the course of the discussion) the specification to which I was required to test these machines had a clause reading as follows: "The generator, when running at full speed and rated load, shall be able to withstand a short circuit at its terminals, without displacing its windings or occasioning any other mechanical injury in any part of the generator." The date of the specification was 1903, and I made the tests in 1904, when the machines were completed, and all six of the machines passed the test perfectly. There is nothing very remarkable that the tests should have been successfully withstood, for in that case the machines were constructed from the point of view of avoiding any such occurrences, and the purchasers evidently had had experience of the matter in still earlier years, *i.e.*, prior to 1903. Consequently, we may safely say that knowledge of the phenomenon and of satisfactory mechanical designs to withstand short-circuiting, dates back at least eight or ten years. In fact, Professor Thompson suggested it many years ago, and in the machines I mention we have a case a good many years ago, where it was evidently recognised that trouble had occurred in practice. At the time the matter was so interesting to me that an article was written by myself and Mr. Punga* fully describing the machines and the tests on sudden short circuit. My proposed remedy is described in an article by Mr. Punga.† In these two articles are

* *Elektrische Kraftbetriebe und Bahnen*, vol. 5, pp. 541, 567, 588, and 611, 1907.
† *Electrician*, vol. 57, p. 765, 1906.

Mr. Hobart. described just such phenomena as the author has described in his interesting paper, though less in detail, because most of my tests were carried out from the rough commercial standpoint, whereas his tests have been made with deliberation and have evidently occupied a good deal of time. We made tests with the oscillograph, and got the ripples which he described, but what was most remarkable to me was the *lasting* proclivity of this current. It took a considerable fraction of a minute to die down. It must have taken anywhere from 15 seconds to 30 seconds for the current to fall from its initial value of some eight to ten times the rated current, as determined by ordinary rough switchboard instruments, down to normal short-circuit value of some three times the rated current. On a later occasion on which I encountered an interesting experience of the breakdown of the end connections of a large turbo-driven alternator, my observations of the utter wreck occasioned in a machine designed without any knowledge of these phenomena, fully confirms the author's experience with his machines. The deplorable part is that it should be necessary for each manufacturer independently to gain his own experience at so great a cost, even after the phenomena are well known in many quarters.

Mr. Cooper. Mr. J. S. S. Cooper: The problem of adequately supporting and clamping the windings to resist the shocks due to faulty switching, or to accidents in the distributing system, has risen to its present prominence only since the advent of large turbo-alternators. The phenomena observed have provided a series of disagreeable surprises for designers, as each succeeding champion winding has been laid low by the enormous sudden forces which characterise the effect in question. In the design of a winding, a first controlling factor is the shape of the slot. Many windings, for example those shown in Figs. 13, 24, and 25 in the paper, are suitable for open slots only. The semi-closed slots have many advantages too valuable to be easily abandoned, and very good windings have been developed especially for use with them. Figs. 18 and 19 in the paper show one which has proved very satisfactory. An easily clamped winding suitable for open slots has been produced by the American Westinghouse Company. A view of it is shown in Fig. A. It is an involute winding in one tier, with all coils alike, and as there is no spacing between different phases, the coils must be insulated for full voltage. The coils are made in halves, and are dropped in the slots and secured in the usual way by wedges. The

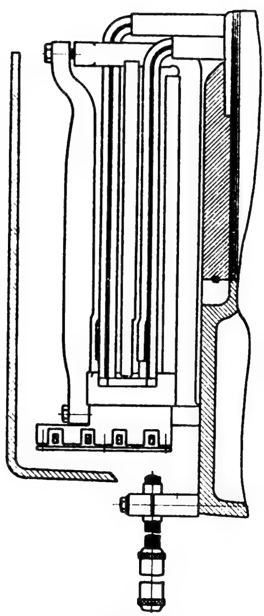


Fig. B.

Fig. A.

half-coils are then connected up at the outer ends. The whole is very flat and compact, and is exceptionally well held by the simple radial clamps. A side view of a clamp with its coil is seen in Fig. B. It Mr. Cooper.

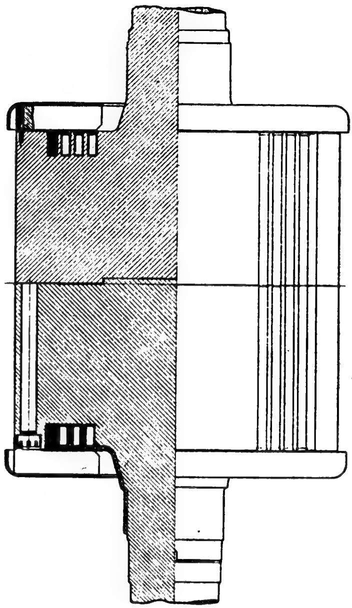


Fig. D.

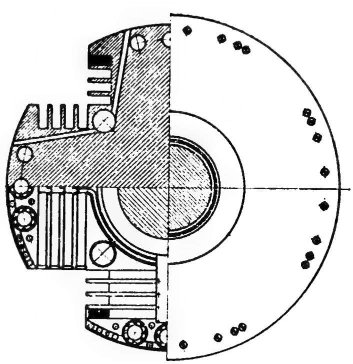


Fig. C.

will be noted that the bolts are quite short, a feature that adds considerably to the stiffness of the winding as a whole. At the beginning of his second paper Mr. Walker has explained an ideal distribution of rotor material. Departures from this ideal are necessitated, not only by

Mr. Cooper. the problem of holding on the copper, but also by the requirements of ventilation and the need of a shaft. If it is desired to extend as far as possible the output for high speeds, the general question of mechanical strength is one of the first to be considered. The laminated type of rotor shown in Figs. 6, 7, 11, and 12 has in this connection the very valuable feature that the iron is an integral piece from the pole surface right down to the shaft. Other designs often embody the dovetailing or keying on of either poles or pole-tips. While entirely satisfactory machines have been built with these methods, it is obvious that such machines must reach a mechanical limit sooner than those in which there are no joints to pull asunder. Another jointless construction is the forged steel field, of which an example is seen in Fig. 3 in the paper. This type has recently been developed to a remarkable extent by the American Westinghouse Company. It is plain that the existence of a hole for the shaft is a possible source of weakness, so the first step was to forge the shaft up in one piece with the rotor. With larger sizes this became too formidable a task, and for 4-pole fields the next step gives the construction shown in Figs. C and D. The field is in two halves, each forged in one piece with half of the shaft. The two are registered together by a spigot, and held by three large bolts running through the face of each pole. In other cases this method has been modified by introducing a main central portion of the field, to each end of which is bolted a short length, which is forged with one end of the shaft. In a 2-pole field the shaft interferes seriously with the space available for winding. This is seen in Fig. E, where the shading indicates the part of the field that can be wound. If the shaft could be removed, the winding might be extended over the space between the two shaded areas. This has been done in the manner shown in Figs. F and G. It will be seen that the field proper consists of a simple cylindrical forging of steel, the winding of which, sunk in machined slots, is carried right across the centre. After this part is wound, the flanges which carry the shaft are fastened to either end of the field cylinder by massive screws, four in number, placed in the field-face where the winding does not extend. If these flanges were of magnetic material, they would cause excessive magnetic leakage. They are therefore made of bronze. In the case shown in the figures, the shaft ends in a boss, which is machined up very much like a huge bevel wheel with dovetailed teeth. The bronze is then cast round this boss, filling the dovetails between the teeth and making a rigid connection. In other cases the flanges have been shrunk or pressed on the inner ends of the shaft. The rigidity of this apparently bold construction is shown by the fact that in running up to a speed of 3,000 to

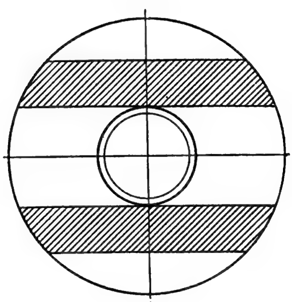


Fig. E.

3,600 revs. per minute the first critical speed is never reached. In machines which have a through shaft of the ordinary kind carrying Mr. Cooper.

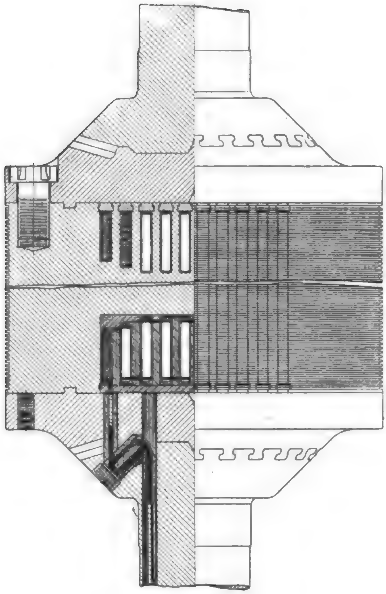


FIG. G.

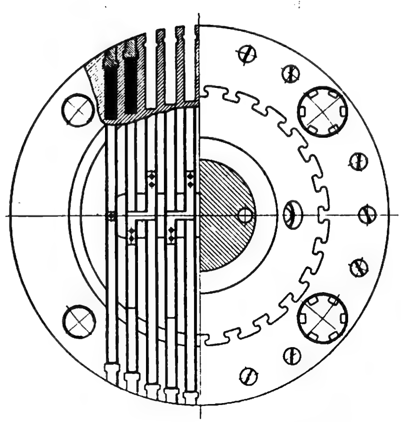


FIG. F.

the field, there is often some difficulty in getting the critical speed up to the necessary 60 or 70 per cent. of the running speed. Machines of the type shown have now been built with an output of between

Mr. Cooper. 2,000 and 3,000 k.w. at 3,600 revs. per minute. This, of course, has never been approached by European makers, but it is only fair to say that in general this type makes a larger machine for a given output than does the laminated smooth-core type of field advocated in the paper. The author's method of compensation * has proved eminently well suited for use in turbo-alternators. A very considerable number of these machines is now in operation, and on ordinary loads it is found that there is no need whatever for special regulating devices. It is to be noted that this result is achieved without making a short circuit any more dangerous than in the case of a rather poorly regulating machine. An ordinary machine of good regulation would probably suffer more from such a mishap than one of the compensated type. The compensation is also instantaneous, a result not to be attained by outside regulators. One of the machines referred to in the paper is now installed in a large station together with machines of standard type, with which it runs perfectly in parallel. It is interesting to note that this compensated set has become the especial pet of the night-shift switchboard attendants, who appreciate the privilege of leaving the rheostats in peace, and knowing that the voltmeter needle will rest tranquilly on its mark.

Discussion at Meeting of March 17, 1910.

Mr. Law. Mr. A. H. Law: I think we are all agreed that the two papers which Mr. Miles Walker has contributed to the Institution records this year leave very little to be criticised, but I think probably some of us can add a certain amount from our own experience which may be of interest to the members of the Institution. With regard to Mr. Walker's paper on the designs of rotors I have very little to say. I should just like to mention that, as Mr. Walker in his other paper refers to Mr. Charles Brown as being the originator of one of the schemes for the end windings of an alternator, I think we ought also to give Mr. Charles Brown credit for the design of rotor for which Mr. Walker is the apologist in his paper, *i.e.*, the barrel type of rotor with a more or less distributed winding round the periphery. Mr. Charles Brown took out a patent for this kind of rotor in 1901, and a rotor of this type built by Messrs. Brown Boveri & Co. at about that time is still in operation at the Neptune Bank Station of the Newcastle Electric Supply Company. It has run satisfactorily ever since it was started up. This type of rotor is really an adaptation of the old single-phase revolving armature designed by Mr. Parsons for coupling to the earlier steam turbines and running in a 2- or 4-pole field. The difficulties in a revolving magnet are greater inasmuch as, for a given output, it must carry at least twice the amount of copper that is required for an armature. On the other hand, the armature being generally designed for a high voltage, insulation difficulties are more prominent, and consequently it will be found that in most cases the designs of these barrel rotors very closely

* *Journal of the Institution of Electrical Engineers*, vol. 34, p. 402, 1905.

Mr. Law.

follow the old single-phase revolving armature, of which numerous examples are running in different parts of the country. Before passing on to Mr. Walker's other paper I should like to thank him particularly for his delightful conception of the ideal rotor in Fig. 1. Passing on to Mr. Walker's paper on short circuits, I should like to ask if he could give us a little more explanation about his theory which would account for the want of symmetry of the wave-form of an alternator immediately after it has been short-circuited. Fig. A shows an oscillogram of a short circuit, the figure being a reproduction from a cinematograph film taken on an alternator during a short circuit. The small straight portion of the line on the left of the upper curve represents the current immediately before the short circuit is applied. You then see a ripple in an upward direction and a very large ripple in the opposite direction. I should like to ask Mr. Walker whether that at all interferes with his theory for the asymmetry of those curves. You will notice the lower vibrations are much greater than the upper ones. I think if we examine the examples given in Mr. Walker's paper it will

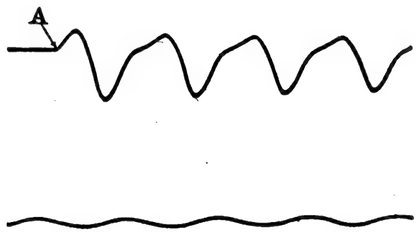


FIG. A.

be found that in all the instances he gives the large vibration is always the first. I may add that this fact was confirmed by an exactly similar test taken on the same machine. The lower curve shows the current flowing after about 6 seconds had elapsed. The short circuit was applied at the point A, and it will be noticed that in the figure four waves are shown gradually dying away. It took about 5 or 6 seconds before a steady amount of current was reached. That current is shown to the same scale in the lower line. These are reproductions from curves of the machine of which I propose shortly to show the end windings.

The President.

The PRESIDENT: What was the voltage at which you short-circuited?

Mr. Law.

Mr. LAW: 5,800, which is the full normal working voltage of the plant. I was going to describe those tests later. I would like in connection with that voltage to ask Mr. Miles Walker whether the tests in his paper were all applied at about one-third to one-half of the normal voltage of the machine. The test I have described was made at the Carville Power Station by the engineers of the Newcastle Electric Supply Company and their consulting engineers and ourselves, and the plant was of 4,000-k.w. output. Fig. C illustrates the windings of the alternator on which the tests were made. The clamping arrange-

Mr. Law. ments are shown. These proved entirely adequate to withstand the alternator being short-circuited at the voltage of 5,800. The first test was made at a lower voltage of 4,000 in order to see if any movement was likely to take place, and on the second test we ran up to full voltage before applying the short circuit. The end windings were all tied up with lead wires to different parts of the frame in order that the movement of the windings might be measured, and after the tests these lead wires were all found to be somewhat slack. The lateral displacement of the wires was measured—that is, the amount through which they could be moved out of their originally straight position. The stretch of the wire within its elastic limit was also allowed for, and it was found that the movement of the coils amounted to about $\frac{1}{32}$ in. It is a

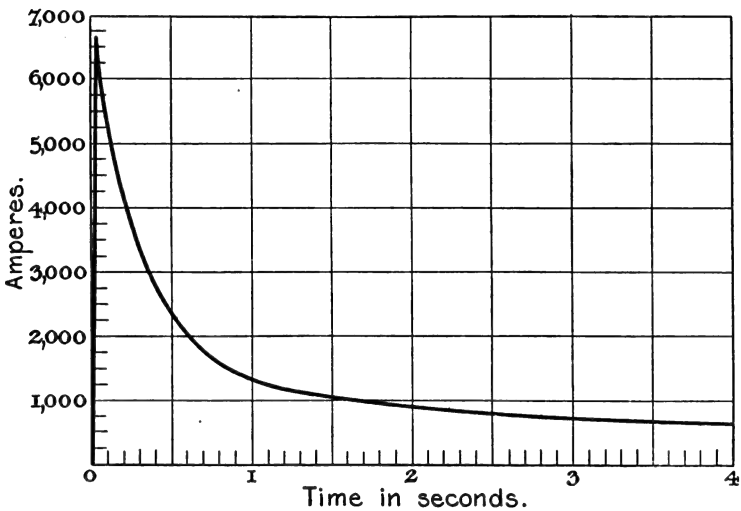


FIG. B.

curious thing that we were all under the impression that the movement was greater, but that is a very common optical effect when watching rapidly moving bodies. Fig. B represents the rate at which the current grew and died out after the short circuit was applied. It is timed in seconds, the end of the scale being 4 seconds. On the left you have the current rising in about the first twentieth of a second to nearly 8,000 amperes and falling in about 1 second to only slightly above its normal value. But even in 4 seconds it had not quite reached a steady value. The alternator on being short-circuited gave out a deep musical note, beginning very suddenly, and it was estimated at the time that this lasted for about $\frac{3}{4}$ second, dying away more or less gradually. I should like to refer to the method of supporting the coils adopted in this alternator. This was a combination of Figs. 20 and 23 in Mr.

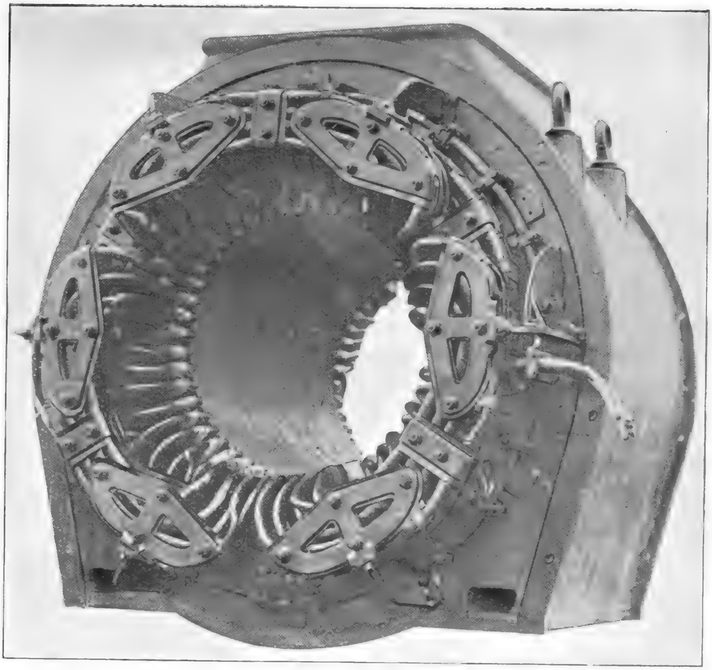


FIG. C.

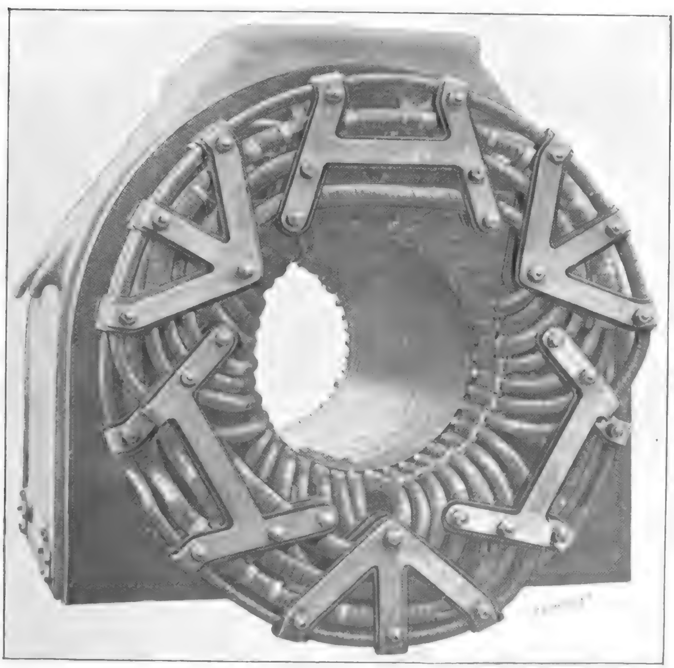


FIG. D.

Miles Walker's paper; that is to say, there were bolts passing through the coils and, in addition to these bolts, cast-iron clamps were included, which braced the ends of the bolts and the windings as a whole to the casing. I think an interesting method was used in this alternator to be quite certain of obtaining a factor of safety. The clamps were made of cast iron in the first instance with the deliberate intention of substituting cast steel afterwards in any event, and this is going to be done on these alternators. In this way, since we know the cast-iron clamps have stood up against the shocks which were imposed in the alternator by short-circuiting at full voltage, by putting in cast steel we also know that we have a factor of safety of at least 3 under the same conditions. In two instances, within my own recollection, have alternators been subjected to these very heavy stresses. One of these was a 2,000-k.w. alternator which was paralleled out of phase. It happened about five years ago. It was paralleled in on top of several much larger alternators. In that case the supports were damaged considerably, but the winding was not broken down, and the alternator ran for some weeks before the damage was repaired. The other instance was a 1,500-k.w. 2-pole plant which was twice paralleled entirely out of phase with several larger plants. This was done owing to a mistake in coupling up the synchronising lamps, but this latter alternator withstood the test without any damage having ensued. I am not quite clear, but there seems to be a prevalent impression that 2-pole windings are very much more difficult to support than 4-pole. I would not like to say that is not the case, but I am not at all certain it is—for if it be granted that a 2-pole winding has twice the stress in it, it must also be granted that it has twice the length on which to fit clamps. The ampere-turns for a given diameter of rotor or stator are limited by heating and other considerations. Therefore it appears to me that a 2-pole winding, offering, as it does, greater length on which to fit clamps, does not present much greater difficulty than the 4-pole. That, I think, is borne out by a certain amount of experience. On page 313 of his paper Mr. Miles Walker draws attention to the importance of keeping down the short-circuit current: "It is possible to keep down the ratio of field ampere-turns to armature ampere-turns, and yet secure extremely good regulation by adopting a suitable distribution of material in the machine." I think that is a fact the importance of which has not been recognised as much as it ought to be. One method he suggests is a special shape of slot. I should like to ask whether that shape of slot really presents advantages. It is true it increases the self-induction of the winding, but does it not at the same time increase the harmful self-induction, producing additional voltage drop? Would it not be better to use the extra space, which is, if I may use the term, wasted on the thick parts? I will just refer you to the Fig. 26 on page 313. A large amount of iron is shown at the inner diameter of the stator. Would it not be better to use that space for putting additional wires into the armature and to increase the self-induction of the armature in that way instead of attempting to increase Mr. Law.

Mr. Law. it by increasing the leakage across the front of the slots? Some makers, including Messrs. Parsons, prefer to use a competely closed slot, partly for the reason that it does undoubtedly limit the short-circuit current and also gives a more mechanical support to the coils. In Mr. Miles Walker's remarks on limiting the short-circuit current, I think he is referring to some form by which the alternator may be designed for very poor regulation under normal conditions and yet have some special means for keeping the voltage variations within a reasonable amount. One of the best known methods for doing this is Mr. Miles Walker's own alternator compounding, which has been fitted with conspicuous success on a large number of machines. For the same purpose an arrangement has been introduced for compounding the alternator by means of the exciter and enabling an alternator to be designed for very poor regulation with, at the same time, a good regulation at the terminals. Messrs. Parsons have recently designed a 1,500-k.w. alternator to run at 3,000 revs. per minute, in which I expect the momentary short-circuit current will not exceed from 12 to 14 times the normal, while at the same time a regulation not exceeding 8 per cent. will be obtained when throwing on the full load with a power factor of 0·8; that is to say, the regulation is about one-fourth of what would be obtained with the best ordinary type of alternator, for in these it is usual to guarantee about 30 per cent. when throwing on full-load current. In other words, the regulation of the alternator will be about 8 per cent. when throwing on *full load* in kilowatts, which is a very different thing to 30 per cent. when throwing on *full-load current*. Fig. D shows the end windings of this alternator. This machine has a 2-pole rotor and runs at 3,000 revs. per minute. It is of 1,500 k.w., and the ampere-turns in the armature are so increased that the sustained short-circuit current will be less than twice the normal, while the momentary will not exceed fourteen times, against the twenty-five to thirty times of an ordinary alternator.

I have very little to add except in regard to short circuits on continuous-current machines. One such instance of this has come within my own experience. This was a 300-k.w. direct-current turbine dynamo which was originally built as the experimental machine for trying Messrs. Parsons' compensating windings. Being the first machine of its type, it had an unusually large amount of compensating winding, and when being tested a short time ago the dipping-plates of the artificial load on which the dynamo was being tested accidentally came in contact with one another, causing an absolute short circuit which was maintained for some time. The effect on the compensating winding was extraordinary. It pulled itself in about a ¼ in. each side, tore away the bolts holding the pole-pieces, and pulled up the armature so quickly that the commutator went on about a quarter of a turn; the armature, however, was stopped without causing any damage except that the commutator sheared its driving keys, and also broke away some of the connections between itself and the winding. This shows the extraordinary effect of a short circuit on continuous-current machines.

Dr. M. KAHN: I must congratulate Mr. Miles Walker on his paper, in which the main difficulties met with in the design and construction of large turbo-alternators have been treated in a most excellent and complete manner. The problem offered by short circuits in large turbo-alternator units is a particularly difficult one, as the coils which have to be rigidly clamped consist largely of insulating material, which, as we all know, is mechanically very weak. There is only one way out of the difficulty, and that is to attack the problem thoroughly, to employ really very heavy clamping arrangements, and not be afraid of getting the clamps close up to the winding. I am borne out in this by one of Mr. Law's diagrams, where it is clearly shown that the big metal brackets are close to the winding. The most suitable windings for fixing are those similar to the windings used on direct-current armatures, either an ordinary barrel winding or an end winding corresponding to the so-called butterfly connections on direct-current Dr. Kahn.

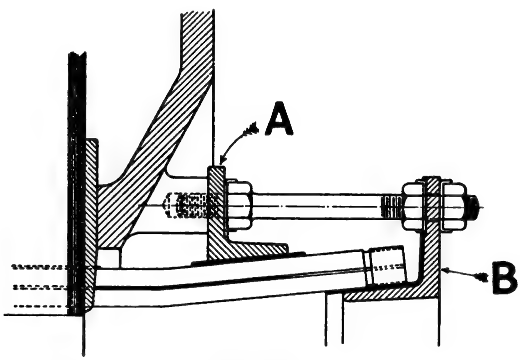


FIG. E.

machines. A method of supporting a barrel winding is shown in Fig. 11 of the paper, but this method requires bolts going right through the winding, which has the disadvantage that the most valuable feature of the barrel winding (namely, that all the bars lie close to one another and form one compact mass) is lost where the bolts pass through the winding. Further, the bars are not all the same shape, which is a disadvantage from the point of view of spare parts. Fig. E shows a method of fixing this winding that avoids this disadvantage. The winding is stayed against movement outwards in a similar way to that shown in Fig. 11, by a supporting ring, A, while a wrought-iron flanged ring B, with pure mica insulation, is forced inside, and wedged to the other rings by bolt outside the winding. This type of construction has been used on a number of machines for some years, and has never given the slightest trouble. I think it is the strongest winding that can be imagined, as all bars lie flat against one another, so that the attraction between bars cannot produce any deformation of the winding, and, in addition, the current in one layer flows in an

Dr. Kahn. opposite direction to the current in the other layer, which has a neutralising effect, as Mr. Miles Walker has already stated (see Fig. F). A number of such machines have been made, and there has never been any difficulty with this class of winding. If the end connections are bent outwards at an angle of 90°, we get a similar winding lying flat against the stator face, which has already been shown by Mr. Cooper last Thursday. A third form of winding which is very often adopted is that shown in Fig. 18 of the paper, called "winding in three tiers." This winding is used very largely, and has the advantage that there is only a comparatively small voltage between adjacent strips, whereas in the case of the barrel winding, the full voltage exists between adjacent top and bottom layers. This merit from the point of view of electrical breakdown is, however, a weakness from the mechanical

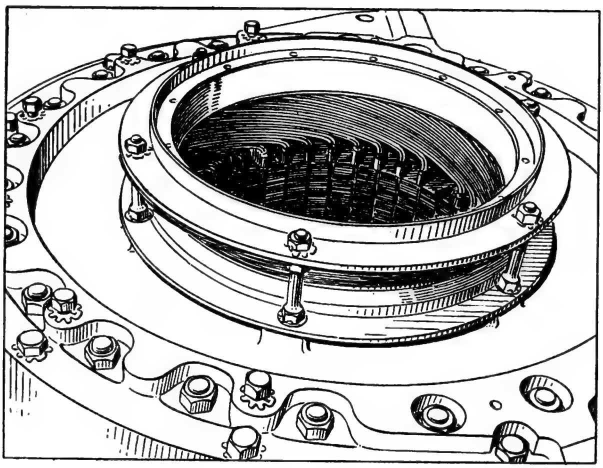


FIG. F.

point of view. Mr. Law has explained that this difficulty can be overcome by heavy clamps, but I think the trouble which has been experienced in this type of winding has been very often due not only to the fact that the whole winding was not properly clamped, but also to the fact that the coils were not stayed against one another. In case of short circuit there are very heavy forces exerted between the different coils, especially on the straight part of the coils where they leave the slots, as there is here a very large overhang, and in the case of short circuits the windings would otherwise be bent together and the mica tubes damaged. Fig. G shows a simple method of construction of distance-pieces for this part of the winding. The distance-pieces are made in halves, both halves being screwed together so that they grip the tubes well at each end and cannot shift. It may be worth mentioning in connection with this type of winding that it is advisable to make the inner

bolts of non-magnetic material, as otherwise they are liable to get hot. In the case of machines of large output one has usually to deal with fairly large currents, which require conductors of considerable cross-section. If these conductors are made of solid copper, they themselves offer a certain resistance against deformation. Such conductors can, however, only be used on former-wound machines, and in this respect former-wound machines have an advantage over machines which are hand-wound with flexible cable. Professor Thompson has already indicated that such former-wound machines with open slots can be used without fear of deformation of the current wave if the slots are inclined at an angle to the axis of the machine. Dr. Kahn.

Mr. Miles Walker has only treated the problem offered by synchronous machines. For large turbo-alternators, the use of asynchronous machines has certain advantages, and one of them is that if an asynchronous machine is short-circuited the total impressed volts are counterbalanced by the reactance voltage, and therefore we do not get

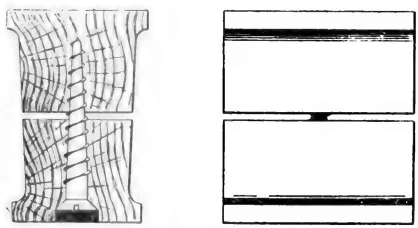


FIG. G.

the big difference between the momentary and permanent short-circuit currents. As the short-circuit current of asynchronous machines is usually about six times the full-load current, the current to be dealt with in the case of these machines is smaller than in the case of synchronous machines of normal design. In addition, the short circuit automatically cuts off the magnetising current of the machine, so that the flux will begin to die away instantaneously.

Mr. J. H. RIDER : I am not able to discuss this paper from its scientific point of view, but having had to examine what effects short circuits have on large alternators, I thought my experiences might be of interest. The reasons which caused the two short circuits to which I am about to refer had better not be gone into, but the fact remains that we had a bad short circuit on a slow-speed 3-phase generator of 3,500 k.w. running at 94 revolutions, due to bad paralleling. The machine had coils similar to those shown in Fig. 9 of the paper, coils of the open type unsupported at the ends. Practically the whole of the end windings of these coils collapsed inwards to the frame of the machine, of course cracking the mica tubes, and breaking the machine down. The other short circuit happened on a 5,000-k.w. turbo-alternator. In that case the effect of the short circuit was rather marked. Mr. Rider.

Mr Rider. The alternator was coupled to the turbine by a large coupling in the usual way, which had 16 bolts 1 in. in diameter holding the two halves of the coupling together. The instant the short circuit took place the whole of these bolts were cut through as with a knife. I have one of the bolts here which perhaps the members might like to see afterwards. You will notice that the shear is as clean as possible. You can just see where the metal gave slightly and then there was a clean shear through the bolts. If you try to work out the energy which would shear sixteen 1-in. bolts in the fraction of a second you will see that Mr. Walker has not in any way over-emphasised the forces which come into play when short circuits take place. I have described the effect upon the coupling. You might ask what was the effect upon the alternator. The alternator is of the type shown in Fig. 23. I do not know if it is a picture of the exact machine, but it is a picture of one like it. It is a 4-pole machine running at 750 revs. per minute, made by Dick, Kerr & Co., and the coils and clamps are of the simple kind shown in the figure. Not a single coil moved so far as we know, not a single clamp was disturbed, the machine was on load again as soon as we put in new bolts, and nothing has been done to the machine from that time to this. I think that is a splendid testimonial to the character of the work, particularly when you consider the apparent simplicity of the clamps. These clamps should be compared with those shown upon a machine which we are now erecting at our power house at Greenwich. It is Fig. 19 in the paper, which is a photograph of a Westinghouse alternator. While I am not quarrelling with the number of clamps Mr. Walker has put on this machine, because no doubt he understands far better than I do the strains to which the machine may be subjected, I think the comparison between the coil supports of those two machines is very remarkable, and I would like to know whether as many clamps as Mr. Walker has provided are really required. It is not in the number of clamps that safety is obtained, but in the placing of the clamps in the right position. You may put clamps all round your machine, but if they are in the wrong place they will be of no use; and I would like to ask Mr. Walker whether it is a fact that, under these short circuits, the coils may be expected to bend inwards towards the core as in the case I mentioned before of the 94-revolution machine. If so, then the large clamps outside the coils do not serve much useful purpose. Turning for a moment to Mr. Walker's second paper on the design of turbo field-magnets, as is well known there are two types now in the market, the ordinary salient pole type and the cylindrical type. It seems to me that one of the disadvantages of the cylindrical type is that you have to use external or additional fans for the purpose of cooling the machine. A salient pole field will create its own draught and does not require any additional fans, whereas a cylindrical type of field does require fans for getting the necessary ventilation. I should like to ask Mr. Miles Walker in connection with the relative advantages of salient pole and cylindrical field systems, 'Is it a fact

that cylindrical type fields require more energy to excite them for a given magnetic effect than salient pole fields?" If he says, "No," than I shall have to ask him why it is that the machine which his company has supplied to us requires very nearly 50 per cent. more energy in the field than another which is of the salient pole field type, which has the same number of slots in the stator, the same number of turns in the coils, and the same speed. On page 330 Mr. Walker refers to the compensating principle which he has designed and, I believe, adopted with great success in many of his machines. It is one thing to use a single machine with a compounding effect or to use a number of machines all with the same compounding effect, but how will a machine with a large compounding effect work in parallel with a number of other machines, all of large size, which have not this compounding effect? I do not know myself because I have not yet tried; I shall know more in a few months' time, but perhaps Mr. Miles Walker could tell us, as I think it would be useful. Mr. Rider

Mr. E. H. Rayner: I cannot criticise these papers from a practical point of view; it is not in my line, but there are one or two physical matters which have struck my attention. The first is with regard to the paper on short circuits, page 303, where we have this very curious phenomenon of a pulsating curve almost all on one side of the centre line. That at once reminded me of some curves I saw in Paris a few months ago. There the same phenomenon was produced in a very different manner, viz., by suddenly switching on a transformer with a considerable capacity in the circuit. I have some curves which have been sent me from the laboratory in Paris, representing some of the work done by Mr. David there, and I thought they would be interesting to the meeting. The first few show some effects which do not exactly bear on the paper, but they will help us in studying the later ones. They show the effect of switching on 10,000 volts generated by a machine which was supplying a cable network and aerial line, some 64 miles long, about one-fourth of which was underground. This shows the important thing from the point of view of the paper, the effect on the current of switching on a transformer. The regular curve in the middle was the voltage of the machine and the other was the current into the line (Fig. H). You will notice particularly that this extraordinary dissymmetrical arrangement was obtained in which you get the ripple only on one side of the curve. Moreover, the intercept on the horizontal axis is about one-third distant when it goes down and up again than when it comes up and down again. In Fig. I the voltage curve is very slightly rippled when the transformer, at 11,000 volts, 25 cycles, is switched on. There is an enormous rise in the current at once, right off the scale at the top, and immediately, with some intervening ripples, it runs right down off the paper at the bottom. Then it comes up again and just passes the horizontal line and goes right back off the diagram again. You will see this effect lasts some considerable time and then the switch is opened at the end. There is very little change for a considerable time in this part that goes Mr. Rayner.

Mr. Rayner. just above the line. The voltage curve is hardly altered. This is a 200-k.w. transformer, light load, 3-phase. This current so surprised the people when they obtained it, that they reduced the current

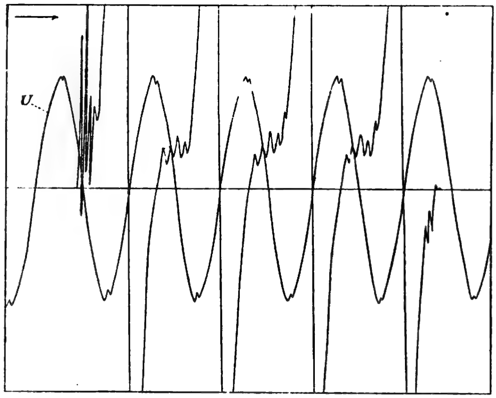


Fig. H.

density on the oscillograph, and obtained something corresponding to Mr. Miles Walker's result, showing the long time required for this current to get anything like to its steady state. I understood when

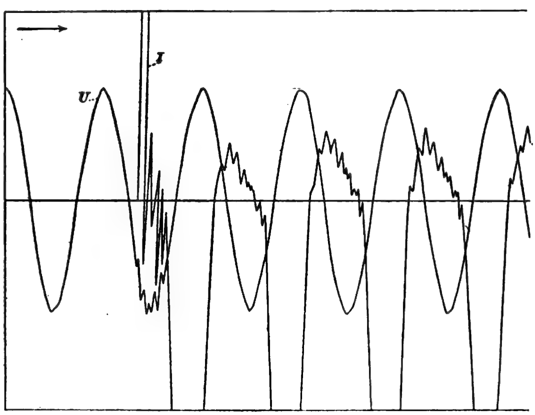


Fig. I.

I was in Paris that this was quite new work on this subject, but I see from the paper it was published in 1904, so it may not be quite new to some of the members. Fig. J is a similar curve of the switching on of the transformer. As one would imagine, this effect depends entirely on the phase of the voltage at which you switch the trans-

Mr. Rayner.

former on, and here the current scale is greatly reduced in magnitude and you see a considerable difference in the ripple. That ripple is dependent on the 11th and 13th harmonics. In the paper which has been published by the Société Internationale all the figures of these harmonics are given, and how they are analysed in the original machine. For 20 or 30 periods the kick at the bottom is quite conspicuous and it takes a long time for it to die out. They make no assumptions as to the cause of it, but they consider it possibly due to the state of the iron in which the transformer was last left

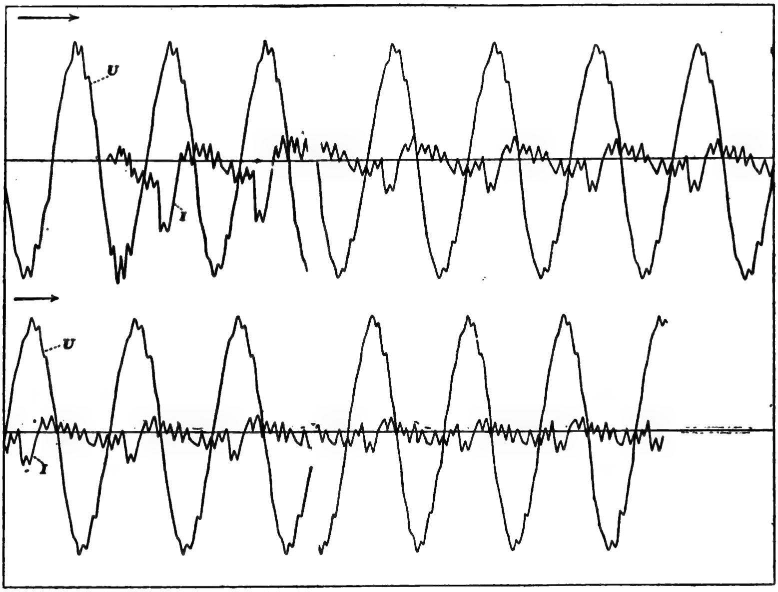


FIG. J.

Note.—Thirteen waves are omitted in the break in the top line and twelve in the bottom line. The right end of the top line is continuous with the left end of the bottom line. From first to last thirty-seven waves are included, and the current curve has not become symmetrical.

before switched on. It seems to me it might also be due to the tremendous electrical jerk that the transformer gets when it is switched on. That could be checked by running the volts down to quite a low value before switching off, and then switching on again.*

On page 305 we have this question of slow-speed machines against high-speed, in which case we have 8,000 ampere-turns on the one machine and 2,000 ampere-turns on the other. That means in these

* My attention has recently been drawn to a paper by Professor J. A. Fleming dealing with this subject, but without the aid of the oscillograph. *Journal of the Institution of Electrical Engineers*, vol. 21, p. 677, 1892.

Mr. Rayner. machines the heating per cubic foot of iron in the stator must be very much greater than in slow-speed machines, and I imagine that is the great trouble now in front of designers—the trouble of getting rid of the heat from the windings. The figure Mr. Miles Walker gives for a machine in one of the papers mentions the fact that in a 3-phase machine or some 5,000 or 6,000 k.w., in each of the three phases you have about 5 k.w. of energy being wasted. That energy from a comparatively small quantity of metal has to get through somehow many thicknesses of insulating material. Five k.w. would heat a good-sized house all the winter very comfortably, yet in each of these three phases there are 5 k.w. I hope we shall have a paper from Mr. Miles Walker regarding stators of these turbo-generators which have to be made so small and in which the ventilation, I think, must finally prove by far the most difficult matter. In the paper on the barrel winding, for instance, he says he can get 2½ times the current density in his barrel winding for the same temperature rise; in other words, he is getting rid of something like six times the watts for his barrel winding for the same amount of copper as he is from the other; that again means that the heat has to come out, and as all the heat goes through the ventilating ducts on the stator, it must add to the difficulties of its design. I should like to know also whether a regulation with 2 per cent. governing really gives no trouble in running machines in parallel.

Mr. Stoney. Mr. G. STONEY: The results brought forward by Mr. Miles Walker with regard to the enormous effects of these short-circuit curves in large alternators are of exceeding interest. In our own experience at Carville, where we short-circuited the 4,000-k.w. alternators at full voltage, the unsymmetrical nature of the short-circuit current about the neutral line came on us as a surprise, and until Mr. Walker's explanation of why the current curve was all on one side of the zero line, we felt very considerable doubts about the accuracy of our results; but his explanation—that a continuous current superimposed on an alternating is really what is obtained—seems quite satisfactory. One matter which I think is of special interest, which Mr. Walker points out, is that in a large station where you have a number of turbo-alternators running one may get double what may be called the ordinary short-circuit current where one machine is put in out of phase—that is, instead of having, say, twenty times the normal current, there is something like forty times, or the stresses may rise to 1,600 times the normal stress at full load, and therefore the short-circuit test at full voltage is really hardly a sufficient test on the windings. A machine ought properly to be thrown in out of phase when all the others are running parallel. I think, however, that this is probably a rather excessive test, and also rather risky to the rest of the station, but this is, as I understand from Mr. Walker, the worst case that could take place.

Mr. Turner. Mr. P. W. TURNER: I should like to say a few words regarding the design of turbo field-magnets. It is known that it is the rotor of a turbo set, and not so much the steam turbine itself, which limits the

Mr. Turner.

capacity that can be obtained from a turbo set at a given speed. For this reason the A.E.G. have evolved a unique design of rotor, with which they are able to attain a very high peripheral velocity of the rotor—no less than 110 metres per second, which is over 4 miles per minute. Turbo-generators up to 3,000-k.w. capacity can now be made, and are made in the A.E.G. works to run at 3,000 revs. per minute. Fig. K shows a section through a bipolar rotor core. The centre portion—the rotor core—is one solid forging of steel forged in one piece with the shaft. Such a rotor core in itself with the shaft has been made in one piece having a weight of 28½ tons. You will notice that the teeth forming the slots and shown in black are altogether separate from the core itself. The coils are seen in the slots, and above the coils steel or gun-metal wedges are pressed in. These teeth are dovetailed into slots milled into the core.

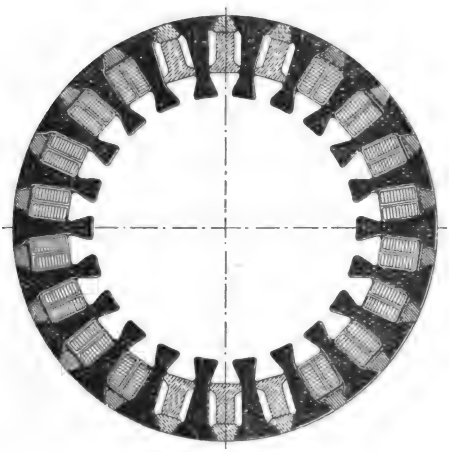


FIG. K.

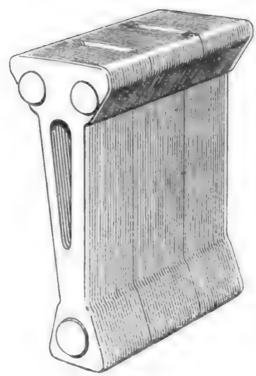


FIG. L.

Fig. L shows one of the bunches of teeth above referred to; these are made in short lengths of about 8 in. long, a number of them forming the teeth in one section of the rotor. These teeth are made of steel plates riveted together. From each batch a certain number are tested for tensile strength, ductility, etc., before they are built up in the rotor. Such pieces have a minimum test of about 38 tons per square inch at the point of fracture. The working stresses which, by reason of the simple construction of the rotor can be very accurately calculated, are only about 4·5 tons per square inch, so there is an ample factor of safety of about 9. Fig. M. shows the coils of the rotor. These consist of copper strip, wound on edge in a lathe, insulated with mica. After being taped and shellaced they are then encased in three air-tight brass cases after having been baked in a vacuum drying-pan for some time. Simultaneously with this baking process, the coils are subjected to high

Mr. Turner. mechanical pressures in all directions, after which treatment they have the constitution of a solid block. When enclosed in the metal cases, insulation pressure tests can be made on each set of individual coils before it is built up.

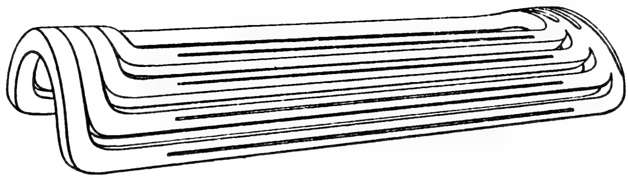


FIG. M.

Fig. N. shows a rotor partly completed. You see there the coils and the wedges forming the teeth in position. This is before the binding process has been completed, and also before the wedges have been driven in. It is almost like a Chinese puzzle to solve how the rotor is built up and wound. It is quite an impossibility to put the teeth

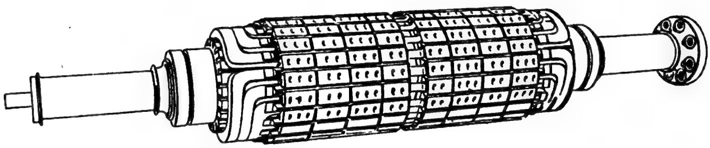


FIG. N.

in the core after the coils have been placed in position, or to insert the coils after the teeth have been put in position. What has to be done is that the coils are built up with the teeth externally to the rotor core, and the whole is then slid on to the core—a most wonderful process. Fig O. shows a finished rotor. The banding of the rotor end connec-

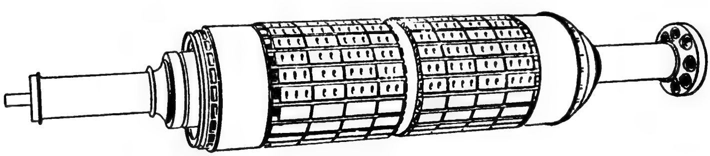


FIG. O.

tions is most carefully carried out. An automatic winding machine fitted with an indicating device at the top regulates the stress in the banding wires, which is maintained absolutely constant throughout the process.

Every rotor is balanced after having been finished, and is then run at 50 per cent. above its full-load speed, which consequently puts a stress on the internal parts of 2¼ times its normal working stress.

After it has been run for some considerable time in this manner it is then balanced again, and should there be any signs of out-of-balance the rotor is rebuilt and has to go through the same process again until no out-of-balance is detected both before and after this high-speed test. In conclusion, I would like to add a remark in regard to the consulting engineer's frequent limitation of the speeds of a turbo-generator set in so many revs. per minute. I consider that that is quite an unscientific basis, having no reference to the peripheral speed of the rotor—which is the figure they wish to keep down—nor has it any reference to the stress inside the rotor core, which, of course, is the important thing. By so limiting the speed the consulting engineers eliminate the better or more highly developed make of machine, lessen the steam economy of the prime mover, and retard the progress of this branch of the electrical industry. Mr. Turner.

Mr. G. W. PARTRIDGE: I think we all owe a debt of gratitude to Mr. Duddell, the inventor of the oscillograph, without which we should have been unable to have seen these most interesting results. There are many points of great interest in Mr. Miles Walker's paper. The flashing of the rotor of the alternator at the time of short circuit, referred to on page 301, is very interesting to me, as I have had exactly the same experience in switching on a large single-phase induction motor. When the switch of the stator of the motor was closed, I noticed flashes took place on the rotor whenever a rush of current occurred when switching on the stator. The forces which are exerted on the windings of large alternators at the time of short circuit are enormous, in some cases, I believe, going up to between 7 and 8 tons on each coil. It is difficult to suggest a method of overcoming this difficulty except, as Mr. Miles Walker suggests, by clamping or holding the stator coils. There is a second method which would reduce the amount of current and which I think is quite worth consideration, and that is by allowing an increase of drop on the alternator. Consulting engineers in the future, I think, should alter their specifications and allow a greater drop on full load on turbo-alternators than they do at the present time. For instance, instead of allowing a drop on an alternator of from 16 to 18 per cent. on a low power factor they should allow a drop of 27 or even 30 per cent. It is quite possible to work with alternators having such a drop, owing to the use of automatic voltage regulators. The old method of hand regulation is really a thing of the past. I have now had over a year's experience of a Tirrill automatic voltage regulator, which is giving most wonderful results, and in future I should not hesitate to allow a drop of from 25 to 30 per cent. on an alternator regulated by this system, depending on the size of the alternator. If the self-induction of alternators were increased in this manner we should diminish the rush of current which takes place on short circuit. Mr. Partridge.

There is a point mentioned by Mr. Miles Walker on page 313, namely, the use of choke coils. I should like to ask him if he thinks the iron in the choke coil would act quickly enough. I rather think he

Mr. Partridge.

would get better results if he used an ordinary resistance. I am not yet in a position to say whether it should be wound inductively or not.

There is a point in connection with the use of large alternators which I should like to refer to. I propose to use two oil switches in series on each generator marked A and B in Fig. P. The switch A short circuits a resistance or choke coil and is controlled by a relay which acts instantaneously; the other switch, B, is controlled by a time-limit relay. When a machine is synchronised, switch A is left open and the resistance acts as a buffer in case of bad synchronism. The switching in and out of the alternator is done by switch B. When the alternator is connected to the busbar switch A is closed. In the event of a short circuit, the instantaneous relay would act and put in a resistance, and tend to choke back the current. It might be said that this relay would not act quickly enough to open the switch A in time; but I am given to understand

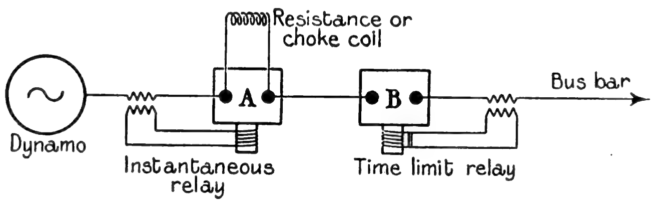


FIG. P.

that relays can be made to act under one-tenth of a second, so that in the case of large alternators where current holds on for a longer period than on small ones, the device I show would be of use in reducing the amount of current on short circuit. A similar arrangement can be used for controlling feeders where heavy overloads or short circuits are likely to take place. I have a similar arrangement in use in connection with a single-phase railway and it has worked very satisfactorily.

Mr. Irwin.

Mr. J. T. IRWIN: I think Mr. Miles Walker has hardly convinced himself that he has large enough forces to account for the effects he has found, and I think, from the tone of their speeches, some of the speakers seem to suggest the same sort of thing. Mr. Walker, in considering the forces acting on the coil, has only taken into account the mutual induction of the coils themselves, and has not taken into account at all the stray fields that might be present and linking with the coils. I am not quite sure of the figure, but I believe that at full load the ampere-turns in armature per pole are about 10,000. If the field ampere-turns were three times as great, we have then got 30,000 or so field ampere-turns. When a short circuit takes place, at the first moment the field strength remains the same as before, but the current in the armature might then be, as Mr. Walker has shown,

twenty times as much as it was before, so that the back ampere-turns are about 200,000, which means that if there was to be the same flux as before the forward ampere-turns require to be 230,000. These turns are supplied by the current in the pole-tips. If we have the forward ampere-turns 230,000 as against 30,000 at normal load, then the magnetic potential at the pole-tip is at least seven times as great as it was before, which means that if under normal running conditions the strength of the stray field was 1,000 lines per square centimetre, under the short-circuit conditions it would be at least 7,000, and there would be the same ratio of increase of all lines of force which had little or no back magnetomotive force. Figs. R and S show the direction of the induced currents in the pole-tip when the current in the armature was lagging 90° behind the E.M.F. The flank leakage shown in Fig. R had practically no magnetomotive force opposing it. Fig. S is a Mr. Irwin.

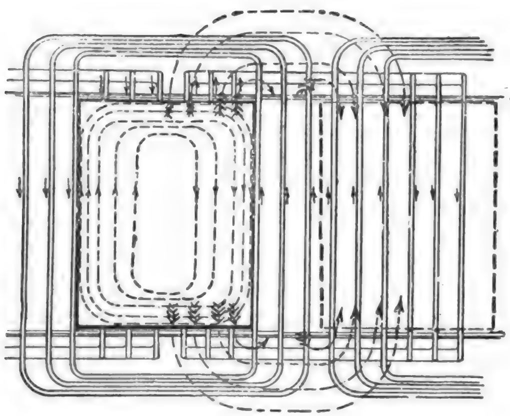


FIG. R.

section through the pole and shows how the field leaked out at the air-gap on account of the strong back magnetomotive force. Now, if we compare the force due to this stray field with the forces due to the mutual action of the coils, we find that in a stray field of a density of 7,000 the force on three conductors, each carrying 10,000 amperes, is 1,400 lbs. per foot run, or about 25 per cent. greater than that due to the mutual action of the coils. If the stray field in normal running was anywhere equal to 1,500, as it might be with a 2-in. air-gap, the stray field at short circuit would be 10,500, and the forces on the conductors would be about 1 ton per foot run. This force is additional to, and not in substitution for, the force mentioned by the author, and the frequencies of the two forces are different. The mutual force between the conductors attains a maximum value in the same direction twice in a complete period, so that the frequency of the force is twice that of the supply. The current in the armature can

Mr. Irwin. be split up into a continuous and an alternating one when we have to consider the forces on the conductors due to a stray field. In so far as there is a continuous current in the armature, there would be a force which reverses in direction every time the coil passes from pole to pole, and the coil would have a force the frequency of which is equal to the supply. In so far as there is an alternating current in the armature, there would be a force which attains a maximum in the same direction twice during a complete cycle, and therefore of the same frequency and phase as the mutual action of the coils. It is probable that most of the damage is done by the alternating stress due to the continuous current in the armature, since the force due to this alternates in direction and would account for the splintering up of wood under the succession of blows. The forces on the conductors

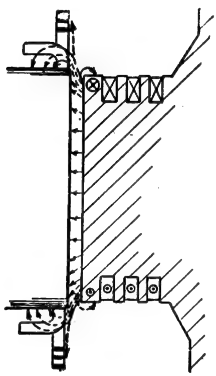


FIG. S.

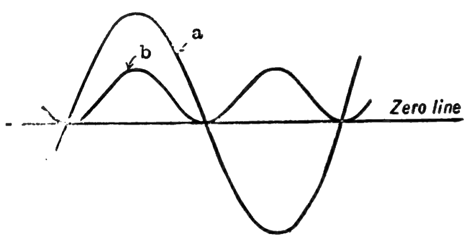


FIG. T.

could be represented by the resultant of the two curves shown in Fig. T, where curve *a* represents the force due to the continuous current in the armature multiplied by the strength of the stray field, and *b* is the resultant of two forces: one, that due to the mutual action of the coils; the other the force due to the alternating current and the stray field.

Mr. Allen. Mr. P. R. ALLEN (*communicated*): Both of Mr. Miles Walker's papers and the interesting discussion they have brought forth turn principally on the phenomena accompanying short circuits on systems fed by turbo-generators, and except for Dr. Rosenberg's remarks in Manchester but little has been said as to what may occur in a station where a number of continuous-current units are coupled up in parallel. For the last few years I have been principally interested in the supply of current for electrolytic processes, and in work of this kind continuous current is of necessity employed, a pressure of about 220 volts being generally adopted as keeping the size of the conductors within reasonable limits, and for the reason of preventing the danger of shocks to the attendants. While this voltage under normal conditions is quite

incapable of piercing any ordinary insulation or jumping any air-gaps, the occurrence of a bad short circuit may produce quite astonishing manifestations in the way of distorting the conductors and starting arcs over long distances. In one instance I have in mind fourteen engines and generators, aggregating nearly 8,000 H.P., are coupled up direct to common busbars, the generators in this case being shunt wound, and having automatic cut-outs on the negative side with knife switches on the positive leads to the switchboard. The circuits leading from the switchboard to the various departments are adequately protected either by automatic cut-outs, or have fuses of a fairly reliable type as the junctions to the smaller branches. On the first occasion that a serious trouble was experienced, the mains leading from the generators to the switchboard, which were laid in a concrete trench and consisted of four sets of two leads each, about 4 in. by $\frac{3}{8}$ in. section, were for about 150 ft. bent and twisted together in a manner which would require enormous force to produce by any mechanical means. This was traced to be due to a dead earth occurring, which in this case corresponded to a short circuit. Though considerable damage was done to the switchboard the generators suffered but little, owing probably to the fact that the circuit breakers were set rather high and only partially operated. Steps were taken after this to prevent the leads actually coming in contact by placing boards between them, and the circuit breakers were set to come out earlier, and for some time things went on all right. However, when the next short circuit occurred the circuit breakers operated very promptly, and while the conductors were not influenced to the same extent, an arc started from the commutator of one of the generators to a brass handrail and continued for quite a perceptible time. This arc measured 8 in., and the fusion marks on the brass handrail can be seen to the present day. In all probability this arc was started in the first instance by particles of burning copper being thrown out from the commutator, and once the arc was started in this manner the voltage required to maintain it was not very high; that is to say, the occurrence appeared more extraordinary than it really was. After the second accident occurred the negative leads on the generators were all taken out of the trench and tapped on to a common negative, while the positive leads were spread further apart and set in separate blue brick conduits. Since then there has been no trouble due to the mutual action of these leads upon each other, although it has occurred on an outlying circuit where the conductors were too close to one another. However, when these difficulties were got over other troubles manifested themselves. Owing to the engines and generators having been put down at various times they are of various makes, run at various speeds, and the machines themselves possess different characteristics, but in the ordinary course of events no trouble is experienced in running them in parallel or in putting them in or out of circuit as occasion may require, the normal procedure being that the incoming machine is run up to its approximate speed with the shunt switch on the magnet circuit closed, and

Mr. Allen.

Mr. Allen. when its voltage corresponds with the voltage on the busbars the main switch is closed on the switchboard and the stop valve on the engine is opened out to follow up with the load. The routine of paralleling is perfectly understood by all the switchboard attendants and drivers, and up to recently has never been attended by any mishap until a few months ago when attempting to put a 1,000-H.P. engine on to the system. The generator was run up to 200 revs. per minute, which was the normal speed, and the attendants declared most positively that the voltage was only a little below that of the busbars. Nevertheless, simultaneously with closing the main switch, the coupling connecting the armature to the flywheel suddenly burst, and if it had not been that the broken piece of the coupling was confined in the armature by the equalising rings probably a disastrous accident would have occurred. The coupling, although of cast iron, appeared to be of usual quality, and theoretically showed a very ample factor of safety. At the same time the key undoubtedly showed signs of a great and sudden pressure having been applied to it, and there was every indication that an immense resistance had been suddenly introduced, which tended to stop the rotation of the flywheel. At the time this happened the circuit breakers on the majority of the other engines came out, and on one machine an arc formed and bridged over from one set of brush-holders to another; and it will be generally found that where a number of continuous-current machines are coupled in parallel, a sudden rise of voltage will always cause a jumping across on one particular machine which happens to afford the most convenient path. In the particular instance referred to, a close examination of the damaged armature failed to reveal any appearance of a short circuit on the machine itself, nor were there any indications that anything abnormal occurred at the moment on any other part of the system. Unfortunately the machine was not tested immediately afterwards to see whether the magnets had got reversed, but there seems no apparent reason why they should have been. As an alternative explanation it has been suggested that the switch was closed with the incoming machine at either a much higher or a much lower voltage than that of the busbars; it seems, however, hardly reasonable that the damage done could be accounted for in this way, but that a severe and sudden shock was thrown upon the machine remains an undoubted fact. Naturally the matter was discussed at considerable length with the makers, but I regret to say that no conclusive opinion was arrived at as to what really happened. I mention these occurrences with a view to confirming the opinion that there is just as much danger of a serious breakdown taking place in a large low-tension continuous-current station as on an alternating system working at a much higher voltage, the matter apparently resolving itself into a question of the horse-power that can be liberated in either case in a given instant. In electrochemical works, which are perhaps at the present time the largest users of continuous-current in bulk, naked conductors are largely employed, and there is usually a general

leakage all over the system from the vats, baths, or furnaces. This in itself is somewhat conducive to breakdowns, but is almost inevitable, and under the circumstances the best precautions to adopt would appear to be to divide the generators into groups of moderate size. Where this is impossible or it is necessary to couple the generators to common busbars, the circuits leading from the switchboards to the work should be protected by adequate automatic cut-outs. The conductors leading from the switchboard to the generator should be either taped or enclosed in such troughing or protected conduit so that it is impossible for them to get either accidentally bridged across by falling spanners or crane ropes, or to become accidentally short-circuited through burst water pipes. With regard to the automatic cut-outs protecting the generators themselves, if these act too quickly apparently the rise of pressure on the system is very much intensified, and if the cut-outs are fitted with magnetic blow-outs, a comparatively weak field should be employed. If two automatic cut-outs are employed or one double-pole cut-out, it is desirable that one side should be fitted with a reverse-current attachment to prevent the machine being put in if by any chance it has got reversed. Minimum cut-outs are of little use, as in the majority of instances they will fail to operate if there is an instantaneous reverse of current, although acting perfectly if the machine is gradually slowed down. These remarks are rather of a negative character, but the point I have in my mind is that the young engineer going to take charge of a large continuous-current station should realise that the phenomena which take place on a bad short circuit or sudden interruption of the current are even now by no means clearly understood, and that the avoidance of short circuits between the switchboard and the generators should be secured by all possible means. There does not seem to be any advantage in introducing time-limit devices on the generator cut-out, as, obviously, when the current has risen to a certain amount above the normal the sooner the circuit breaker acts the better, but the point is that the circuit breaker, when it does act, should break as gradually as possible, and the form of breaker in which one contact is broken after the other ending on carbon tips seems the least likely to give rise to sudden surges on the system. Mr. Allen.

Mr. J. C. MACFARLANE (*communicated*): I do not think it is generally known that the instantaneous currents in the stator windings of large alternating-current generators, when the armature is short-circuited at full speed and excitation, rise to such enormous values as indicated in the first paper. It is interesting to note that the author does not appear to think there is any diminution of the main field flux at the moment of short circuit, due to the armature reaction, because of the fact that the eddy currents produced in the pole-faces and field windings react on the armature. It is assumed in the paper that the armature reaction at the moment of short circuit will only create a cross-magnetising effect; this, however, cannot actually be the case, as it would appear that in all cases in practice there must be a certain amount of lag at Mr. Macfarlane

Mr. Macfarlane.

the moment of and during short circuit. This being the case, the armature demagnetises the field to some extent, and although the action may largely be damped out by the eddy currents in the poles and exciting windings, there must be some diminution in the field in order to create these eddy currents. It is therefore surprising that the instantaneous currents are as large as indicated by the diagrams. With regard to the forces acting on the stator end windings, these are, in all probability, due as much to the actual stray fluxes from the main field path, as to the field produced by their own currents; for it is well known that if a magnetomotive force is suddenly applied in opposition to another, a considerable stray flux is produced between them if the M.M.F.'s are separate. In the cases under consideration the opposition M.M.F.'s are well separated and enormous (probably as much as 10 times the normal field M.M.F.), at the instant of short circuit, and it is probable that due to this action the stray field threading the armature end windings is very great. In any case there appears to be some difficulty in otherwise accounting for the enormous stresses that actually take place. It has been suggested that the end shields protecting the end windings have some effect in diminishing the mechanical distortion due to short circuits, and it would be interesting to know the author's experience in this matter, and further in what directions the bending takes place. With regard to the rise in voltage that may occur when a continuous-current circuit breaker is opened under a heavy current, this phenomenon is very interesting, but the cause of it is at present involved in some uncertainty. As the author states, it is very difficult to produce these high voltages experimentally. I may remark that it is just about as difficult to get rid of them when they do occur in practice. A case apparently of this description was recently brought to my notice, where the circuit breakers when opening, although of the quick-break type, maintained the arc formed at the contacts for a considerable period. Circuit breakers with a larger break were installed, and, so far as I know, the trouble has not recurred. It was also noticed that at the time of opening of the circuit breakers flashes occurred at various parts of the switchboard. It is most desirable to elucidate what conditions of arc, capacity, and self-induction, cause these dangerous voltages, as in all probability a considerable number of cases of machines flashing over may be due to this.

Turning now to the second paper, I thoroughly agree with the author that the cylindrical type of field magnet is the best from most points of view. I have experimented with direct-current armatures in which the iron loss is only a small fraction of the copper loss; but in every case the iron took up the heat from the copper, and the temperature rise of the copper and iron was always the same at the end of the test. The circumferential surface of the cylindrical field type of rotor is considerably more valuable as heat dissipating surface than the surfaces formed by the ends of the core and the ventilating ducts, because the heat conducts at a considerably greater rate radially

Mr. Macfarlane.

through, than axially along the core, and in the cylindrical type this surface is much greater than in the salient pole type. As the circumferential surface of the core, from the point of view of the dissipation of heat, is much more valuable than the end and duct surface, it occurred to me to experiment on a new construction of core, in which this cylindrical surface was considerably augmented by building up the armature core with discs of two different diameters—one being slightly greater than the other. Such larger and smaller discs were threaded on the shaft alternately in suitable numbers, thus permitting radiation from the sides of the periphery of the larger core discs, as well as from their edges. The projecting portions of the larger discs were bent slightly to form a core surface capable of producing a violent air-scrubbing effect. It will be seen that if the large diameter discs are pitched $\frac{1}{8}$ in. apart, and they are $\frac{1}{8}$ in. larger in radius than the small discs, the total circumferential surface is increased to three times that of a plain core. By the construction described it will be understood that any air immediately adjacent to the armature, and which is therefore charged with a certain amount of heat therefrom, is during the rotation of the same continually and violently displaced, thereby reducing the temperature of the armature. The circumferential surface of the core, when rotating, approximates to a radiator of a motor-car under way. The results of the initial experiments showed that a core, constructed as above, with a circumferential surface of only twice that of a plain core—but in all other respects similar—got rid of about 25 per cent. more heat than a plain core of the same dimensions, and for the same temperature rise. Considering that in a turbo-alternator the air-gap is large, the rotor has partially closed slots, the length of core is great as compared with the diameter, and the surface speed very high, it should be possible to get rid of 100 per cent. more watts with the construction described above than with a plain core, as it would be easy to raise the circumferential surface to four times that of a plain core. Another method of increasing the radiating surface is to stamp the discs all of the same shape, but to have one or two of the teeth in each disc longer than the others. By suitably mounting the discs, it is possible to arrange helical passages round the circumference of the core, which might be an advantage in driving the air along the surface of the core, much in the same way as done by a propeller fan. I would like to ask the author whether he has any definite information as to the number and width of ventilating ducts necessary to give the best results from all points of view, bearing in mind that each ventilating duct means a certain amount of useless copper in both the stator and rotor, and adds to the length of the machine. It appears that the rotor core shown in Fig. 6 is not well ventilated from the point of view of getting air to the ventilating ducts; nor is the surface of the core at each side of the ventilating ducts fully used, owing to the longitudinal holes in the core being so near the outer circumference. Turning to Fig. 12, there does not appear to be any method of getting air into these round holes. Probably the greatest advantage of the cylindrical

Mr. Macfarlane.

type rotor is that a field-form approximating very nearly to sinusoidal can be obtained. I think it would be possible to obtain an exact sinusoidal distribution of flux along the polar arc, by spacing the slots, or by distributing the turns along the polar face according to a sine function. As the armature reaction of a polyphase generator is practically sinusoidal, more especially if partially closed slots are used, and the air-gap and number of slots per pole per phase are large, the resulting flux curve would at all loads be to all intents and purposes sinusoidal. Slight departures from the sinusoidal flux wave-form would be greatly reduced in the voltage wave-form, due to the action of the phase belt, and to the fact that if star-connected, a large number of the harmonics are naturally eliminated. For machines supplying capacity loads the above consideration is of considerable importance, and Mr. Steinmetz has taken out a patent for an armature winding which eliminates some of the harmonics produced, and reduces the others considerably (see U.S.A. Patent, No. 935941, October 5, 1909). The author's curves, Figs. 15 and 16, are extremely interesting, and show clearly another considerable advantage the cylindrical rotor has over the salient pole type.

Dr. Sumpner.

Dr. W. E. Sumpner (*communicated*): Mr. Walker's paper contains the first clear explanation I have seen of the known fact that the alternator currents due to a sudden short circuit are abnormally large and give rise to excessive forces acting on the end connections. The oscillograms of Fig. 5 show that the short-circuit current of a large generator takes a long time (nearly half a minute) to settle down to the steady periodic state, and that at first the current may be quite ten times as great as that corresponding with the normal impedance of the armature. The explanation given is that the armature self-inductance for sudden changes is much less than that corresponding with normal running. This will hardly be disputed, and is of obvious importance when alternators which are badly out of phase are switched in parallel. But it seems equally important in connection with the question of parallel running in general. The theories that have been advanced, to explain hunting effects with alternators, have rarely been supported by experimental evidence, and quite ignore changes in the self-inductance of the machine such as this paper affords evidence of. The sluggish way in which the self-induction alters from its minimum to its normal value is a factor which must be seriously taken account of before a true theory of parallel running can be established.

The paper contains a great number of points which are both novel and important. One of the most interesting is the statement on page 304 of a number of tests relating to the behaviour of the exciting current under various conditions. I do not agree with the remarks on the capacity current made on pages 300 and 301. The curves of Fig. 6 show certain ripples which are attributed to the capacity of the coils. It seems to me they are more likely due to rapid changes in the self-induction or electromotive force caused by the movement of the pole with reference to the slots. A capacity of only 0·028 microfarad

Dr. Sumpner.

cannot cause any appreciable change in the heavy short-circuit current unless the alteration of potential is assumed to be instantaneous, and even in this case the capacity current would not traverse the coils but the path of the short circuit. In any ordinary form of lightning protector (as in Fig. U) in which machinery or apparatus M is protected from a high-potential surge on the line by means of a choking coil Ch, and a spark-gap or electrolytic arrester S.G., it is usually assumed that the function of the arrester S.G. is to discharge the surge while that of the choking coil Ch is to take up all the voltage of the surge by means of its reactance, thus preventing the high potential reaching the coils of the machine M. But this explanation is incomplete because the reactance of the choking coil Ch is much less than that of M, so that if the voltage were distributed in proportion to reactance the coils of M would be subjected to practically the whole voltage. The fact is that the capacity between Ch and earth, although very small, is sufficient under excessively rapid changes of potential to take a large current to earth, and since different portions of this current traverse various lengths of Ch before passing to earth the

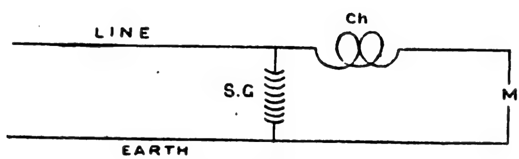


FIG U.

corresponding reactive voltage of Ch relieves M of excessive voltage, and also prevents any appreciable current reaching M at all. The return path of the capacity current is not through M but through the short circuit or spark-gap S.G. A similar effect takes place when an alternator is short-circuited as in Mr. Walker's tests. The short circuit involves an almost instantaneous change of potential at the short circuit, but the return path of the corresponding capacity current must be through the short circuit and not through the coils. This current cannot persist through several oscillations because the condenser plates are short-circuited by conductors of negligible inductance.

Dr. Pohl.

Dr. R. POHL (*communicated*): The developments in high-speed machines are progressing at such a rapid rate and are so important that a frequent discussion of problems connected therewith is highly desirable. It is unlikely, however, that a discussion on the question of cylindrical *versus* salient pole rotors will reveal less disagreement to-day than it did on previous occasions. Highly satisfactory machines of both types have been constructed, and the advocates of the salient pole type can point to recent constructions of large turbo-alternators which disprove any contention that the cylindrical type is being universally adopted. To my mind both have their proper field of employment, and it would be unwise for any one to take a determined stand for

Dr. Pohl. either one or the other. The choice depends chiefly on the output and speed, and is influenced by the exciting voltage and the ratio of field ampere-turns to stator ampere-turns that can be adopted. Mr. Walker appears to have a decided preference for the cylindrical rotor on the grounds: (1) That it corresponds more closely to "the best theoretical arrangement" (Fig. 1) of his paper; (2) that highly saturated teeth represent a better form of magnetic reluctance than a large air-gap; (3) that the copper when arranged in slots can carry about twice as much current per square inch than when arranged in coils 2½ in. in thickness; (4) that the distribution of the rotor winding leads to a good wave-form at all loads; (5) that the cylindrical rotor lends itself easily to the employment of the compounding principle in which the armature reaction strengthens the field; (6) that its leakage factor is smaller than that of the salient pole rotor. With point (1) I do not agree; Fig. 1 cannot be accepted as the best theoretical arrangement without a more complete statement as to the theoretical principles to which this design is claimed to conform most closely. If the object be to obtain a given output in the smallest possible space irrespective of all other considerations, then the axial overhang of the cylindrical winding must at least be taken into account. But if the more practical object of obtaining a given output with the smallest expenditure of material is kept in view, then I contend that the salient pole type represents more closely the ideal section. I entirely agree with the second point, but submit that highly saturated teeth can be, and are being, employed in the salient pole rotor as well as in the cylindrical one. Fig. 2 of the paper is an example of this. In regard to point (3), ventilated or subdivided field coils allow of exceedingly high-current density, especially when wound of flat strip on edge, and Mr. Walker's statement in this respect cannot be taken as generally applicable. With regard to point (4), whilst this is theoretically correct, Mr. Walker will agree that numerous salient pole-type machines with excellent wave-forms are running. Indeed this is not only a matter of rotor design, but it can be largely influenced by the arrangement and distribution of the stator winding. On point (5) there will be general agreement. It stands to Mr. Walker's credit to have proved this conclusively. The results given on page 331 are highly satisfactory considering that the device adopted does not involve any material complications. Unfortunately, however, one has to deal in practice with lower power factors, for which Mr. Walker's simple method is less applicable, so that this point loses in practical importance. Point (6) is of little consequence if one considers that the leakage factor in turbo-alternators is not of very great influence, especially where the field-ampere-turns are reduced by the employment of compounding or automatic regulating devices.

The reasons which in many instances have led to the adoption of the cylindrical type are: The extreme difficulty of adequately accommodating one coil of big section on each pole of 2-pole machines running at 3,000 revs. (this will be at once recognised from a section of such a pole showing the space occupied by the shaft at the ends); the

early trouble of the field coils "working" and throwing the rotor out of balance, which has since been overcome; the difficulty, in machines of very great axial length, of obtaining enough ventilation combined with security of the coils in the centre, which is being overcome with the advent of axial forced ventilation and of dividing the poles into two parts (see Fig. 5 of the paper) which need not be circular in section; the great amount of expensive machining necessary, which is also being reduced with progressing experience. Against this is to be set the smaller weight, smaller length of turn, shorter distance between the bearings, greater accessibility for inspection and repair, and lower cost —points so important as to lead me to the conclusion that the salient pole type is likely to hold the field ultimately except in the case of bipolar machines and of alternators of extreme axial length. I will only add that I prefer external choking coils to any internal construction such as is shown in Fig. 26 of the paper for the purpose of lessening the short-circuit current of alternators. Such oil-immersed choking coils serve the double purpose of making the short-circuit current adjustable and of protecting the stator end coils against the well-known dangers of increased pressure connected with violent load fluctuations. Dr. Pohl.

Mr. A. G. ELLIS (*communicated*): In his paper Mr. Miles Walker makes out a fairly good case for the cylindrical type turbo rotor. One of the principal factors to which he calls attention is the lost space between the poles of a salient pole type rotor, and he states that in a cylindrical rotor a great part of the periphery can be utilised for flux and ampere-turns. While the cylindrical type has some advantage in this direction, it should be observed that the teeth in the neighbourhood of the slots in which the field windings are embedded, carry only a small part of the total flux per pole. These teeth correspond to the interpolar spaces in the salient pole type and are of little use electromagnetically. Their chief function is to retain the windings and to permit of the centrifugal force of the coils being distributed, and they impede the ventilation as compared with the interpolar spaces of the definite pole type which assist the ventilation, especially in 4-pole machines. I have had some experience with the type of rotor illustrated in Fig. 5 of the paper. The principal advantage of this type is its extreme simplicity. As each of the pole elements is of circular section there is no lateral component of the centrifugal force of the copper on the sides of the poles which can produce bulging. This dispenses at once with the need for any angle brackets or wedges between the poles, and leaves more room available for the copper and a clear space for the ventilation. The ventilation is further enhanced by the large spaces between the poles at the centre of the machine, and by providing a wide duct in the stator at the centre a better air circulation can be obtained, I believe, than is possible with a long cylindrical drum having a number of small ducts fed from lateral tunnels. It is not an easy matter to get air through a drum rotor when the core length exceeds 1 meter. With the circular pole type rotor Mr. Ellis

Mr. Ellis. (Fig. 5) it is possible to work at high-current densities in the field copper and, given good ventilation, I would question the statement on page 324 that "copper placed in slots can carry twice as many ampere-turns per inch as copper wound in a coil 2½ in. in thickness." The whole question, apart from the mechanical side of the problem, depends on the ventilation of the field windings, on which the total number of ampere-turns which it is possible to get on the field depends. The circular pole type has one disadvantage, namely, that for a given stator bore the maximum diameter of the pole and the length of the armature core are practically at once determined, and thus there is only one *natural* rating corresponding to each diameter of stator bore. This circumstance renders it desirable to employ a greater number of standard diameters than is necessary with other types. If one has, for example, only two or three standard diameters for 4-pole machines up to 5,000 or 6,000 k.v.a., there are certain ratings for which it is very difficult to arrive at an economical design of this type. Another point is that the ratio of the pole section to the polar surface at the air-gap is smaller than in the salient pole type with rectangular poles or with the cylindrical type, which leads to lower values for the average density per square inch of air-gap surface. This is, however, compensated for by the better ventilation and by there being more winding space available than is the case in constructions such as are shown in Figs. 3 and 4; hence the armature periphery can be more heavily loaded with ampere-turns per inch, and no reduction in output results. As regards pressure regulation, if one compares the salient pole type with the *non-compensated* cylindrical type the former is more advantageous. As Mr. Walker states on page 329 of his paper, the pressure regulation depends on the ratio of the field to armature ampere-turns and on the shape of the saturation curve. The more flat the saturation curve becomes the lower may be the ratio of field to armature ampere-turns, or, as the problem resolves itself for turbos, for a given rotor carrying its maximum possible ampere-turns per pole, the higher may be the armature ampere-turns per pole and the output of the machine. Now, in spite of the danger limit of saturation of the poles to which Mr. Walker calls attention, it has been my experience that the high quality steel which it is necessary to employ for turbo rotors is so reliable magnetically that one can without much risk saturate the poles very highly and obtain a very flat curve. One can reach values for the saturation factor, as defined by Dr. Kloss,* as high as 65 per cent., and it is practicable to work with a ratio of field to armature ampere-turns much lower than two for normal degrees of pressure regulation. With the cylindrical type, as Mr. Walker observes, the saturation curve does not bend over as in a machine with highly saturated poles. It is, in fact, prohibited to work at high points on the saturation curve of the machine, as one soon reaches the limiting flux densities in the armature core and teeth consistent with the heating limit. Hence for the same degrees of pressure regulation it is necessary

* *Journal of the Institution of Electrical Engineers*, vol. 42, p. 167, 1909.

to employ a higher ratio of field to armature ampere-turns, which offsets the gain in utilisation of space on the rotor effected by the cylindrical construction. Of course, these remarks do not apply to a compensated machine of the type which Mr. Walker has developed. It is interesting to hear that Mr. Walker considers a 15,000-k.v.a. unit at 1,500 revs. per minute, with 4 poles, a practical proposition. I had come to the conclusion that 10,000 k.v.a. would be about the limiting output of a 4-pole 1,500 revs. per minute machine of the definite pole construction in the present state of turbo design. The author's figure of 1,000 ampere conductors per inch (page 331) seems to be very high, and it is certainly much higher than can be reached in a non-compensated machine, as the available winding space on the rotor would be inadequate for the necessary field ampere-turns with a diameter of only 44 in. Mr. Ellis.

Mr. J. E. GRANT (*communicated*): The oscillograph records which Mr. Miles Walker exhibited, showing the effect of closing and opening an alternating electrical circuit upon a machine winding and line, reminded me of an analogous effect upon a hydraulic system. Some time ago I experienced great trouble owing to the pressure gauges failing and the cylinders bursting unaccountably. The gauges on the presses were made for twice the working pressure, and the presses were generously proportioned. One day whilst watching the presses working I noticed that at certain times when the pressure was put on, the gauge showed a momentarily greater pressure than the accumulator was supposed to give. This I thought I could understand. The thing I could not understand was that at the moment of opening to exhaust, the gauge sometimes jumped up to more than 50 per cent. above the working pressure. This happened only when the three-throw pumps were pumping up the accumulator, and therefore regular pulsations took place which, had they been recorded, would probably have resulted in a diagram like that shown in Fig. V. The jump which showed on Mr. Grant.

FIG. V.

the gauge did not take place every time the press was exhausted, even when the pumps were working, and possibly it was only when the pulsation was on the up grade that it did take place. I ought to explain that although the inlet valve is closed before the exhaust is opened, yet the pulsations are, of course, transmitted through the metal which intervenes.

DISCUSSION AT MANCHESTER, MARCH 8, 1910.

Mr. M. B. FIELD: I am very glad that we have got this paper from Mr. Walker at last. I have been waiting for it for some four years. In February, 1906, I read a paper before this Section of the Institution dealing with the distribution of current in armature conductors. Mr. Field.

Mr. Field. I also referred briefly to the Chelsea alternators, mentioning that on several occasions the end-windings had been destroyed under short-circuit conditions. I can remember quite well that on that occasion Mr. Peck called attention to the fact that although I had commented upon the breakages of the windings I had not referred to their latest method for supporting them, which he was confident was going to be thoroughly successful, and it is interesting to see from Mr. Walker's paper that they have had no further trouble since this new method of supporting the end-windings was introduced. The destruction of dynamo windings, twisting of conductors and busbars, and similar phenomena which occur under violent short-circuit conditions, have been experienced by most engineers dealing with large central stations, and it is interesting to see exactly where this destructive energy comes from, because it does not necessarily come from the prime mover itself. Mr. Walker has divided the short-circuit current into two components—a continuous-current component and an alternating-current component. In the curves he threw upon the screen you notice that immediately after a short circuit the crest of the negative after-waves—*i.e.*, the lowest points of the oscillating current—just touch the final horizontal zero line, which means that the initial *continuous* current had a value of about half of the maximum value of the actual total current. Now, this continuous current is due purely to the energy stored in a magnetic state in the alternator at the moment of short circuit, and is not produced by the energy of rotation. The energy stored in a magnetic state in the alternator must be dissipated on short circuit, and it can be dissipated either as heat in the windings due to the flow of the current or it may be dissipated partly as heat and partly as actual mechanical work done upon the end-windings in bending them up. The initial value of the continuous current being equal to half the maximum value of the current at short circuit, we may ascribe a considerable portion of the damage which results to the continuous-current component which flows, and it is therefore interesting to calculate what is the store of energy in the alternator in the magnetic state at the moment of short circuit quite apart from the storage of energy in the kinetic state—*i.e.*, as energy of rotation. The energy stored in virtue of the magnetism generated in a circuit is equal to $\frac{1}{2}LC^2$, where L is the coefficient of self-induction and C the value of the current flowing, and if we apply this formula to the figures which Mr. Walker gives in his paper we see that the total storage of energy due to the magnetic state of the alternator at the moment of short circuit would lift a good many tons several feet high. There seems, therefore, to be an abundant destructive agency stored up in this form in a machine of this description. It must be very nice to be in the position of having a 5,000 or a 6,000-k.w. alternator or a 500-k.w. rotary converter placed at one's disposal for making such tests as are given in the paper. But I think it must be still more gratifying to the designers and to the owners of the plant to have such confidence in their machines that they can contemplate the repetition of such drastic tests

Mr. Field

with equanimity. At the same time, it would be interesting to know what was happening to the steam turbine at the time. I would like to ask Mr. Walker what load the turbine was giving out under short-circuit conditions before and after matters had settled down to the steady state. On referring to the curve on page 302, there appears to have been considerable variations of speed, judging by the number of semi-undulations which occur in a given time interval, as represented at different parts of the curve. If we can take it that these curves represent the state of affairs correctly and have not been distorted in any way, it will be necessary to account for considerable speed variations taking place in a very short space of time, and I would like to hear Mr. Walker's explanation of this point. Mr. Walker has further raised in his paper the question of sparking at the bolt-heads of the rotor of the turbine. This puts me in mind of a similar instance to which my attention was called some considerable time ago. In a certain sub-station in London there are a number of motor-generators; the motors have short-circuited rotors and the sets are run up to speed from the direct-current side when the stator winding of the motor is switched on to the alternating-current busbars. The effect that was noticed was that at the moment of switching-on there was a heavy thud in the machine, which is not altogether to be wondered at, but the curious thing was that on certain occasions a flash was seen somewhere in the rotor. No damage was done by this flash, and when the machine was standing still no mark of any description could be seen on the windings of the rotor. Further, this winding being of the squirrel-cage type, it always seemed very remarkable that there could be any voltages of sufficient magnitude induced to cause flashing. It was perfectly obvious that it was not static effect. Now, I do not know the exact construction of the rotors in question, but Mr. Walker's paper suggests to me that the phenomenon may be similar to the instance he has cited. There might be, for instance, heavy eddy currents induced in some bolts clamping up the rotor plates and sparking occurring between the ends of these bolts and the end clamping rings owing to bad contact. At first sight one would have thought that the squirrel-cage winding would have effectually choked back the flux and have prevented it from inducing a heavy current in any bolts located at a lower level, but one must remember that the flashing that Mr. Walker refers to was at the bolt-heads, which were 2 in. below the surface of the solid pole. Lastly, I would like to make a few remarks with regard to the capacity effect noticeable in Fig. 8. Taking the positive half-wave at the moment the switch is closed, one notices a very small irregularity in it, and also small irregularities in the crest of each positive or upper half-wave. These are so small that one's attention has to be called to them or they might escape notice. The matter interests me because I found exactly similar irregularities in certain experiments I was making for the paper I read in 1903 before the Glasgow Local Section. On that occasion I was photographing the oscillatory discharge in circuits containing capacity and self-induction, and when

Mr. Field. using a certain coil as my self-induction I obtained the ordinary oscillatory charge of the well-known shape, viz., an alternating current gradually dying down according to the logarithmic law. I then put in circuit a transformer, using one winding only as the self-induction, and with this in the circuit I obtained these curious irregularities on the curve. I was quite at a loss to explain the irregularities for some time, until it was pointed out to me that they were caused by the sideways capacity effect of the transformer which I had included in the circuit —*i.e.*, the capacity between primary and secondary and between winding and earth. The result of this was to give rise to an exceedingly high-frequency term in the discharge which was superimposed upon the relatively low-frequency discharge which I was looking for. The case is exactly analogous to the results obtained by Mr. Walker, the high-frequency effect in Fig. 8 being due to sideways capacity between the winding of the generator and earth. At the same time, it is not altogether clear to me at the moment of speaking why these irregularities seem to be only present in the upper or positive half-waves, and I would like to know from Mr. Walker whether this is actually the case or whether similar irregularities were present in the lower half-waves as well.

Mr. Cramp. Mr. W. CRAMP: I have little to say as regards the means for preventing tremendous forces from bending the end-connections by additional supports, because the matter lies in the hands of designers who are more experienced than I am; but, besides this, there are suggestions in the paper for minimising the forces set up, by reducing the short-circuit current, and upon this idea I wish to make a few remarks. There is very little difference between short-circuiting a generator and applying an E.M.F. suddenly to an inductive circuit. Now, in the latter case expressions are obtained similar to those found in the paper at the bottom of page 299. If these are considered closely, I think it will be found that the maximum possible current that can flow when the worst conditions are considered, and with a circuit of constant permeability, is about twice the normal current of the circuit. Mr. Walker, however, has spoken of ten times the normal short-circuit current, from which it follows that the great rush is due to the varying permeability accounted for by eddy currents, and the fact that the field magnets are revolving in front of the coils. If the two terms of the mathematical expression be considered, it will appear that the current in excess of twice the normal short-circuit current can only be due to variations in the exponential term, which then represents a line far from straight.

Towards the end of the paper there is a suggestion that to get rid of the great forces the self-induction of the circuit might be increased. I would like to ask Mr. Walker if from the considerations above, putting extra self-induction in circuit, so far from actually decreasing the current rush, might not, in certain cases, even tend to increase it, and whether it would not be better to try and render the permeability of the circuit more constant by non-salient poles, lower saturations, and

Mr. Cramp.

a smaller flux per pole? Frequency will also have a great effect in determining the maximum value of the rush. The higher the frequency the greater should be this initial rush of current, according to theory. It would be of interest, I think, if Mr. Walker would explain the reason why the initial rush is thought to be smaller with higher frequencies, and wherein lies the discrepancy between theory and practice in this matter. There is another consideration which seems to have been left out of the paper altogether, and that is the effect of the other two phases which are at the same time short-circuited, for the paper apparently treats the matter as a single-phase problem, which would seem to be a mistake. Will not the three phases when short-circuited produce a single synchronously rotating reaction with the field due to the exponential current (if one may use the term) superposed thereon?

Professor Marchant.

Professor E. W. MARCHANT: The first point to which I wish to refer is armature inductance due to slot leakage. The effect of armature reaction proper has no time to penetrate into the rotor at the first instant of short circuit because of the eddy currents induced in the rotor core. Some time ago Mr. Catterson Smith and myself made some tests on two 2,000-k.w. turbo-alternators at Liverpool. The object of these experiments was to investigate the triple-frequency currents that flowed through these machines when they were connected in parallel. The machines were star-wound, and were rated at 200 amperes per phase, and the triple-frequency current was nearly 60 amperes in the neutral line between them. The results of these tests were published in August of last year, and they give a very simple method of determining the slot leakage reactance. If the magnetising effect of the triple-frequency currents is worked out for a 3-phase machine, they will be found to balance each other as far as armature reaction is concerned. We made some calculations by analysing the potential difference wave so as to determine the magnitude of the triple-frequency component of potential difference. The result gave a value for the self-induction per phase of 0·0037 henry, or a reactance of 1·17 ohm. The generators were star-wound for a line pressure of 6,000 volts, and the short-circuit current would therefore be 2,960 amperes, or approximately 15 times the full-load current. This result corresponds fairly closely with the figures given by Mr. Walker, though it must be remembered that the estimate makes assumptions that are incorrect. For example, the saturation of the iron will be much greater when the short-circuit current passes, and the inductance therefore will be correspondingly diminished. The eddy-current effect which Mr. Walker mentions as tending to increase the apparent impedance of the armature coils will be taken into account by this method of determining slot leakage reactance, though the triple frequency of the testing current will tend to impair the accuracy of the result. All estimates of this kind are very approximate, and it is remarkable that the calculations agree as closely as they do with the tests.

The second point to which I should like to refer is the time taken

Professor Marchant.

by the armature reaction effect to penetrate into the rotor core. Mr. Walker mentions that it takes about a second before the exciting current in the main exciting circuit falls from 70 to 20 amperes due to armature reaction. That statement reminds me of some experiments described by the late Dr. John Hopkinson. He worked with an iron core 11 in. in diameter; the core was wound externally with an exciting coil, and a number of ballistic coils were embedded in the iron, the coils being of varying diameter. The smallest coil placed at the centre of the core was not affected until 20 seconds after the closing of the main circuit. With large masses of iron the time taken for any change in the state of magnetisation to penetrate is very much longer than is generally believed.

Mr. Worrall.

Mr. G. W. WORRALL: The variation in the period of the wave, noted by Mr. Field, is sometimes due to a variation in the speed of the oscillograph drum. This is caused by the friction between the trigger and the disc which operate the shutter in the "Duddell" type of instrument. In Fig. 7 the period is very much reduced at the end of the record; such a change frequently occurs on the portion of the film which lies between the drum surface and the spool. Although I have not the slightest doubt that due precautions were taken to use the oscillograph at the critical damping temperature, the little peak which occurs just after switching on is characteristic of an under-damped instrument. Mr. Walker's experiments appear to consist entirely of short circuits following open circuit. I think that the conditions of a short circuit following full load would be somewhat different. In the first place, the rate of change of current immediately following short circuit would be influenced by the rate of change immediately preceding it, for any change in the rate of change of current is opposed by the inductance, hence the steeper the current wave at the instant of short circuit the greater will be the rush of current which follows. In the second place, the phase of the current wave in oscillation to the potential difference wave on load will influence the short-circuit current, for if the short circuit takes place at a given point in the current wave, the position of the poles in relation to the armature coils at the given instant will depend upon the phase of the current in relation to the potential difference. Still a third way in which the load current would influence the short-circuit current is the magnetic condition of the armature at the time of the short circuit. The influence of the armature capacity on the higher harmonics is shown by the distortion of the wave in Fig. 6. In this case the capacity is not sufficient to produce resonance, but if the short circuit occurred at the end of a long length of cable, resonance might easily take place, and the higher harmonics in the short-circuit current wave might be of greater magnitude than the wave of fundamental frequency. Mr. Walker has only referred to hard wood clamps for the armature coils. I have seen sheets of mica sewn in canvas bags used.

The opening of a circuit breaker on a direct-current system may set up very violent surges, and may seriously damage the motors on

Mr. Worrall.

the system. In the case of a 500-volt 3-wire system with which I am acquainted the sparks from an emery wheel caused a deposit of metallic dust on one of the brush-bars of a 500-volt motor; the earth opened one circuit breaker, and the inductance and capacity of the other motors caused a rise of voltage to take place which broke down a ⅜-in. air-gap between the brush connectors on the earthed motor and opened the other circuit breaker. The earth burnt itself out, and the switches could be closed and the motor re-started without difficulty. This occurred every few hours until the cause was discovered and the gap between the brush connections was increased. The next time the motor earthed, the arc flashed round the commutator by way of the lugs, and melting the solder, short-circuited most of the segments. In another case a 5,000-volt 100-H.P. 3-phase induction motor was broken down by suddenly switching on; the flash went across a considerable gap between the leads of two phases, and the arc set fire to the insulation. The machine did not go to earth, and no further damage was done.

Dr. Rosenberg.

Dr. E. ROSENBERG: With regard to Mr. Seaton's experiences, it is only just to say that short-circuit troubles are older than turbo-generators, and that engine-type generators are not free from the possibility of damage in case a short circuit occurs. In one respect even, turbo-generators are much better off, namely, as far as damage to the body of the rotor and stator is concerned. Turbo-generators have a comparatively small diameter and a very stiff yoke, besides which, the air-gap between rotor and stator is large. Therefore in case of short-circuiting or even synchronising dead out of phase, hardly any damage is done to the rotor and stator core; the damage is limited to the windings and couplings. The yoke of a large engine-type generator, on the other hand, say with 100 poles, represents, from the mechanical point of view, a beam with a very long span and comparatively weak section. The air-gap between rotor and stator is small, and any inaccuracy in erecting will give a large difference in the air-gaps of two diametrically opposite poles. The forces which come into play when a short circuit or faulty synchronising occurs may then not only wreck the winding, which as a rule in these machines is not so well supported as in a turbo-generator, but also may deform the stator to such a degree that the rotor fouls the stator and does serious damage. I know of this experience from a case which happened about six years ago on 4,000-k.w. generators, which were thrown in parallel dead out of phase. The heavy forces which come into play at the moment of short-circuiting—that means in the moment when the armature reaction tries to wipe out suddenly the magnetic field—are comparable with the big electrical forces coming into play when the field current is suddenly switched off. We know that in such cases, due to the inertia of the magnetic field, which resists a sudden diminution, the voltage generated in the field coils may be ten times as high as the normal working voltage. If we consider the field as the primary, and the armature as the secondary winding of the transformer, we try in the first case to extinguish the

Dr. Rosenberg.

field by short-circuiting the secondary, in the second case by switching off the primary. The great damage done in cases of short circuits is sometimes due to a generation of high voltage at the moment of the high current. It is not true that in a short-circuited winding no measurable voltage can exist. In the case of 3-phase star-connected generators, for instance, the three terminals of which are short-circuited, quite a considerable voltage may exist between the star-point and the short-circuited point. In direct-current machines which are short-circuited quite unexpected changes happen. The general opinion is that a shunt-wound direct-current generator, at the moment of the short circuit, loses its excitation because there is no voltage impressed on the shunt coils. But this is entirely wrong. The big armature reaction at the moment of short circuit (mainly the demagnetising action of the short-circuit currents under the brushes, which tries to wipe out the field) causes an *increase* of field current although there is no outside voltage impressed, and only very gradually, say in 10 seconds or even more, the field current dies down to zero. On the armature, although at the moment of short circuit the voltage between the brushes is zero, a very high voltage may be induced between points of the commutator approximately midway between the brushes. If we have, say, twenty times normal current flowing through the armature conductors, this gives an enormous field at right angles to the main field, and that will set up in the armature between points which are normally equipotential, a voltage, say, of five times the normal armature voltage. I have no doubt that it is mainly due to this fact that at bad short circuits sometimes an arc is established which goes all round the commutator. It is not only that the current under the brushes is so great that it cannot be commutated, and that therefore an initial arc at the brushes is started. The continuation of the arc is due to the fact that after the commutator bars have passed the brushes the voltage between two bars is very much higher than the ordinary working voltage.

Mr. Everest.

Mr. A. R. EVEREST: The amount of current which flows in the windings at the first instant after short circuit is generally assumed to be determined by the reactance of the windings and the voltage on the machine at the time the short occurs, but we must remember that the winding reactance decreases with very high currents, due to tooth and other saturation, so that with twenty or thirty times full-load current, the reactance becomes much smaller than the value determined around full-load current, and the instantaneous short circuit may be expected to be still larger on this account.

On page 300 there is mention of the instantaneous value of short-circuit current being 7·6 times the value on steady short circuit. Now, the value of current on steady short circuit depends on the amount of excitation. For excitation corresponding to full voltage no load it may be 1·75 times full-load current. With excitation sufficient for full inductive rated load it may be 2·5 times, and with field strength as used on heavy overloads it may be three times full-load current. But

Mr. Everest.

the instantaneous rush of current on a sudden short circuit depends, not on the excitation, but on the actual amount of pole flux, that is, the generated voltage, which is almost constant under the different conditions mentioned. Therefore the ratio between instantaneous and steady short-circuit current values would be much greater if occurring at light loads. For this reason it seems preferable to express the values in terms of rated full-load current as the unit. Mr. Walker has shown us on the screen various methods adopted by leading manufacturers to successfully cope with the enormous forces acting on the stator windings. He has also described cases showing the violent effects in the rotor present in the form of heavy compensating currents which flow in any damping circuits on the rotor, or in the absence of such, in the field winding itself. He has described the heavy arcing which occurred in one case between the bronze end-rings and the bolts holding them to the poles, and in another case the flashing which was seen around parts of a damper when the short circuit was created.

One case is recalled of a salient-pole machine with field windings of edge-wound copper strip, which, being accidentally thrown into a short-circuited feeder, flashed across one field coil, leaving a scarred burned patch about 4 in. long across the surface of the windings. Undoubtedly the rotor surges, both in current and in voltage, may be very severe, and it is to be regretted that Mr. Walker has not made further reference to this important feature of short-circuit phenomena. Few can be disposed to dispute the conclusion expressed in the discussion on Dr. Kloss's paper before this Institution last year, and now again emphasised by Mr. Miles Walker, that large alternators should for self-protection be designed with sufficient reactance to keep the effects of accidental short circuits within reasonable values. The author has shown one method by which close self-regulation may be retained under such conditions. Another familiar and much used device is the Tirrill regulator, by the addition of which a high reactance machine possesses a closeness of self-regulation superior to the closest machines of the ordinary type depending on so-called inherent regulation. The additional reactance desirable for protection can either be internal, or may take the form of choke coils connected to the machine terminals. In this latter arrangement, the coils serve also to protect the machine-windings from high-voltage surges arising externally.

Mr. Watson.

Mr. S. J. Watson: The manner in which the modern multipolar direct-current machine stands up to short-circuiting is very remarkable, bearing in mind the heavy mechanical and electrical stresses to which they must be often subjected under usual working conditions. Without these investigations by Mr. Walker, most of us, I think, would hardly have realised that the short-circuiting current would rise to such a very high value, and in this connection it is particularly of interest to note the appreciable length of time a machine is called upon to carry the overload before the circuit breaker actually comes into play.

Mr. Walker.

Mr. MILES WALKER (*in reply*) : I wish, in the first place, to thank all those who have taken part in the discussion for the new data they have supplied, the constructions for armature windings and field-magnets they have shown, and the many new explanations and ideas that they have introduced. I am sure that we have all benefited from the interchange of thought, and have arrived at a better knowledge of the phenomena that we have been discussing. I am glad that Professor Thompson has pointed out my incorrect use of terms when speaking of the ratio between the maximum value and the virtual value of an electromotive force. We are really in need of a good term to express this ratio. Perhaps Professor Thompson will give us an apt expression which will become a standard, as so many of his terms have already become. The term "output" has been purposely used in connection with field-magnets, in order to emphasise the fact that just as there is a limit to the output of an armature, so with an alternator, furnished with a given field-magnet, and run at a certain speed, there is a certain

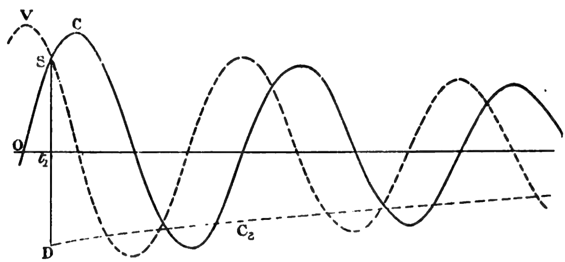


FIG. W.

kilovolt-ampere at a certain power factor which cannot be exceeded by reason of the limits fixed by the two factors considered in the paper.

Mr. Hobart's experiments were very interesting. It was possible that the lamination of the pole-piece, of which he spoke, prevented the great eddy current in the pole. It was the eddy current that produced the curious behaviour of the exciting current described in my paper. Mr. Cooper's remarks were very much to the point, because the critical speed at which serious vibration occurs is a most important consideration in the design, and may often determine whether a certain machine can or cannot be run.

Mr. Law has asked for some further explanation of the want of symmetry of the wave-form of the short-circuit current. A simple way of looking at the matter is the following. First of all consider sinusoidal curves of voltage and current whose amplitudes are at first great, and which gradually decrease as shown in Fig. W, the current C lagging almost 90° behind the voltage V. The first term of the expression for C given in the footnote on page 299 will give us a current wave-form like that in Fig. W. If the short-circuiting switch were

closed at the instant o (that is to say, at the instant when the current would be zero according to this curve), then the current would follow the curve without any displacement of the medial line, and there would be no need for the second term in the expression in the footnote. If, however, the circuit is closed at the instant t_1, then there is superimposed upon the alternating current a continuous current D C_2, whose initial value is equal and opposite to the ordinate t_1 S. This current gradually dies away, being killed by the resistance of the circuit. It is expressed by the second term of the expression given in the footnote. This superimposed current has the effect of making the total current start from zero, which of course it must do, and the alternating current is unsymmetrical (see Fig. X) as long as the continuous current lives. It will be seen that the curve sketched in Fig. X is of the general form of the curve observed by Mr. Law, only his has some higher harmonics in it which probably have been produced by field distortion. Mr. Walker.

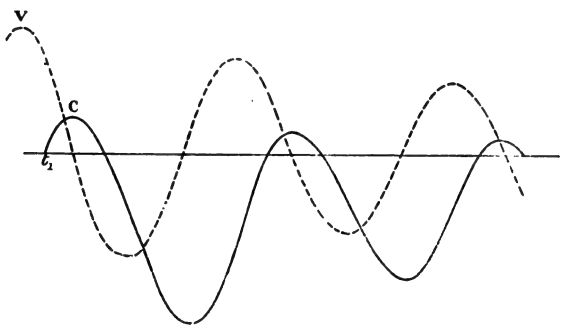


FIG. X.

The reason that we did not carry out our short-circuiting tests at any higher voltage than 7,000 maximum was that, owing to the low self-induction of the winding, the shock to the whole machine, winding, coupling, bedplate, and turbine, was very excessive. The winding was of an old-fashioned type, which could not be trusted to withstand a short circuit at full voltage. The terrific vibration that occurred on short circuit made one have fear even for the bedplate itself. Since the experiments here described were made, quite a number of more modern machines have been short-circuited at full voltage, and have stood up well; in fact, some consulting engineers include in their specification a clause to the effect that the machine must be short-circuited as part of its official test. Although that has been in the past difficult to live up to, we can now, with modern constructions, make windings to stand up perfectly well. With regard to the 2-pole and 4-pole windings, I still think the 2-pole winding is more difficult to construct than the 4-pole winding, for this reason: In a 2-pole winding there are more conductors grouped together in one

Mr. Walker. phase band, and it is the total current passing in the group that determines the force in the bunch of coils.

Mr. Law suggests that instead of making more leakage across the mouth of the slot, we should put more wires in the slot. It must be remembered, however, that the number of ampere wires on a given frame is limited. By increasing the ampere wires 25 per cent., we might destroy the regulating qualities of the machine, but if we merely increase the armature leakage flux from 3 per cent. to 6 per cent. of the working flux, we cut down the short-circuit current to one-half. It is perfectly true that machines can now be made with a very large number of wires in the slots, and a very high armature reaction, and yet with good regulation. When this is done, short-circuit current is not so great as in machines with small armature reaction. Mr. Law's method of compounding with the exciter is an exceedingly beautiful one. It is rather interesting that he has beaten me quite recently in some guarantees, and I congratulate him on that. The statement he made about the 1,500-k.w. alternator, yielding twice full-load current, which would give fourteen times instantaneous current, is, I think, right.

Dr. Kahn has referred to the mica tubes. We know now that the forces are so great that however big may be the clamps put on, there may be a certain amount of movement between the clamps, and flexible insulation is still necessary. One must have fairly flexible insulation as well as very strong clamps. The distance-pieces which Dr. Kahn has shown are now used by quite a number of firms, and they really are very necessary, particularly on the parts of the winding which project from the slots.

I was very much interested in Mr. Rider's remarks and the statement about the bolts having been sheared. It is an illustration of the enormous turning moment which occurs at the instant of short circuit. There is one interesting point about that to which attention should be drawn—namely, that the forces in the coils do not necessarily occur at exactly the same instant as that at which the rotor receives its sudden check; in fact, as we know, the current is lagging about 90° behind the E.M.F. The instant of maximum torque may occur $\frac{1}{4}$ of a period earlier than the instant of maximum force on the coils. The torque and the forces on the coils depend upon the particular phase of the E.M.F. when the short circuit occurs, but they are affected in different ways. It is possible that in a machine the torque tending to stop the rotor is very great, owing to the armature current being in phase with the flux, and yet the current itself is not so great as to destroy the winding. It is possible that windings which have withstood a short circuit once will not withstand a second short circuit occurring at a different phase of the E.M.F. Mr. Rider has suggested that the clamps shown in Fig. 19 are perhaps stronger than need be. I can only say we have had machines with half the number of clamps on in which a certain amount of movement was shown between the coils, and though the winding stood up, extra clamps were advisable.

He also asked if coils always go in. They do not always go in; it depends upon the direction of the current flowing in them. That is why it is necessary to put blocks in between them and bolt straight down. Mr. Rider has said that a cylindrical field requires more blowing. It is perfectly true the salient pole acts as a splendid fan. It must also be admitted that the cylindrical field acts as a good fan—in fact, a great number of cylindrical rotors, such as induction motors, are running without any other fan on them. They ventilate very well, but a greater power may be got out of a machine by putting more air through it, and it has been our practice to put extra fans on. One object of the fan is to direct the current of air over the armature winding. Mr. Rider asks why the machine shown in Fig. 19 requires more exciting current than the machine shown in Fig. 23. I do not want to enter on a controversy. It is sufficient to say that the machine in Fig. 19 regulates better than the machine in Fig. 23. That is the main reason why we have an extremely strong field-magnet. It is only fair to say that the salient pole field has a much less mean turn than the cylindrical field, so that, other things being equal, for a given number of ampere-turns on the salient pole, there will be less exciting loss than in a cylindrical field. But considering that the exciting energy is such a small fraction of the output, what does it matter whether it is ½ per cent. or ¾ per cent., especially if the regulation is very much better? Questions have also been raised by Mr. Rider and other speakers as to how a compensated machine will work in parallel with a non-compensated machine. The experiment has actually been tried in Glasgow, where a 4,000-k.w. machine is running perfectly well in parallel with non-compensated machines. The reason of this is that the compensated machine is not compensated for wattless load, and, as is well known, it is the wattless current which helps in the parallel running. The only effect is this: if a compensated machine be running in parallel with one that is non-compensated, the compensated machine tends to take rather more than its share of the idle power. When an alternator is holding up its volts better than another alternator with which it is running parallel, it does not at all affect the parallel running, but only affects the power factor of the load on that machine. The machine will take rather more than its proper share of the wattless component until it pulls down its voltage to the voltage of the other machines. Mr. Walker

Mr. Rayner's curves are very interesting. The dissymmetry of the curve is due to the switching-on effect. The formula will be found on page 299. With regard to the ripples on the curves, they may be due to three main causes. First of all there are the ripples which are due to the oscillation of a current which springs from the distributed capacity. You find that these die out very soon. In Mr. Rayner's curve you will notice that the ripples do not die out; they keep up for a long time, and that leads me to think that they were not due to a capacity effect, but rather due to harmonics in an electromotive force wave. That is a frequent cause of ripples in currents charging a cable.

Mr. Walker. Supposing the alternator has 12 slots, then ripples may occur in the electromotive force wave. The ripples may be almost invisible at no load and at normal load. But when you throw the generator on to a cable of the right capacity they will all increase, owing to the resonance with the cable. It is just possible that the capacity of this cable is such as to bring out some ripples which were there before, although they were almost invisible. There is a third form of ripple, due to the peculiar behaviour of iron. It is really the same thing, only instead of coming from the alternator it arises from the behaviour of the iron. I do not quite understand Mr. Rayner's remarks about the 5-k.w. loss. A 5-k.w. loss would mean 1 per cent. copper loss, and that is generally rather high for a turbo. I think he must have made some slip there. Generally the loss would only be about $\frac{1}{3}$ of 1 per cent. in the armature. It is perfectly true that it is a problem to get the heat out of the turbo-alternator, because such a large amount of energy is lost in a comparatively small machine. It is, of course, a problem which is always attacked as a question of physics. A certain amount of heat is produced, a certain wall of insulation of a certain area and thickness is provided, and the heat must be got through the wall, and after it has gone through the wall into the iron it then encounters a certain area of cooling surface from which the heat must pass into the air. You have to blow the heat away by putting through plenty of air.

I was most interested in Mr. Turner's pictures of the A.E.G. rotor. I have often admired that machine, but I have never seen such good pictures of it as were shown to-night. I must say, from a theoretical point of view, it stands in the front rank. The winding is well supported; the means of preventing oscillation of the shaft, for keeping up the critical speed-point are good, and many other things in the design are very excellent indeed. I am glad to see they are able to get such large powers and high speed. There is no doubt that as soon as the designer shows that high powers and high speeds can be obtained, the consulting engineers will agree to specify them. Although consulting engineers are very cautious at first, they are generally reasonable.

Mr. Partridge's statement of the description of the choking coil to be put in a circuit before parallel operation is interesting. It was known in the early days of alternators, especially those of rather low self-induction, that considerable advantage was gained by adding self-induction, particularly at the moment of synchronising, and if that self-induction could be cut out afterwards it would be of advantage. Therefore the suggestion he has made of putting in choke coils at the instant of paralleling might be very useful. It might certainly save the machine if the operator made a bad parallel. I think it is quite impossible to make any kind of automatic switch which will put in a choke coil quickly enough to save the machine. I take it that this choke coil is put in before starting to parallel, and then if a bad shot is made, the coil will save the machine, and after paralleling it can be cut out.

Mr. Irwin's contribution to the discussion is most valuable. There is no doubt that the stray field from the eddy current in the pole can produce enormous forces on the ends of the armature coils just where they project from the slots. The bending of the coils at this point is no doubt sometimes due to this. I do not altogether agree with Mr. Irwin's method of calculation of the stray field. The only part of the field that can do harm is the part which is interlinked with the armature conductors, and for the most part the armature ampere-turns oppose the field ampere-turns and prevent the interlinking. There will, however, be cases when stray flux of considerable value from the field magnet extends to the projecting ends. It is interesting to note that one often finds all the conductors of one phase bent together, as though they had attracted one another. When this occurs, one would gather that the main magnetic flux in operation was produced by the currents in the coils themselves. Mr. Irwin's theory serves to explain these cases which do sometimes occur when the end windings are twisted in the direction of rotation. **Mr. Walker**

It is interesting to see from Dr. Pohl's remarks that there is still a great deal to say in favour of the salient pole construction. The shorter mean turn and the simplicity in erection and in making repairs are undoubtedly very great advantages, so that one may expect the controversy on this subject to be continued for many years to come.

Mr. Macfarlane will see that I have considered what happens in a polyphase machine, from the instant when the pole is passing the centre of phase A, the short circuit occurring at that instant. To find what happens in each phase we must apply Fig. 2 to that phase, drawing the zero-line at the right elevation, having regard to the instant of short circuit in relation to the instant at which the pole passes the centre of the coil. If we consider all the phases on any kind of short circuit, we shall see that the first action that takes place is a cross magnetisation. The demagnetisation does not take place until the field has moved round one-half of a pole-pitch, as shown in Fig. 3. Mr. Macfarlane's remarks upon the increasing of the cooling from the surface of the rotor, and the results of the tests he gives are very valuable.

In reply to Mr. Ellis, it is true that for each diameter of machine there is only one length which is most economical, but it is also true that the loss in economy when we depart from that length is very little. Suppose, for instance, that the most economical length for a 40-in. rotor were 50 in. We could build a machine of four-fifths of the output, 40 in. long, or a machine of six-fifths of the output, 60 in. long. The costs of these machines would differ very little from the costs of machines built on smaller and larger diameters respectively having the theoretically correct diameters.

I agree with Mr. Allen that where we have a very large installation of direct- or alternating-current machines, running under conditions which do not make parallel operation imperative, it is best to break up the installation into a number of independent groups. Provision can,

Mr. Walker. of course, be made for running any pair of groups in parallel when this is required.

Dr. Sumpner is right in stating that a capacity of 0·028 microfarad could not cause any appreciable change in the value of the short-circuit current unless the alteration of potential were almost instantaneous. On the closing of a switch the alteration of potential is exceedingly rapid. The shunt for the oscillograph was placed in series with a conductor which connected the 3-pole switch of the generator to the short-circuiting point, that point being kept at earth potential. The capacity current would pass through part of the winding and be recorded by the oscillograph. In the case where the short circuit occurred when the voltage was near its maximum, the first rush of current seems to have been made up not only of the capacity current, but also of current flowing through the whole armature. We know that for very high frequencies a circuit will not have its self-induction increased by being surrounded by iron, even if that iron is laminated in the ordinary way. This is because at very high frequencies the eddy currents in the iron act as the secondary in a transformer. Now it may be that the self-induction of the armature winding (which we have taken as being mainly due to slot leakage) is for these first rushes of current very much smaller than we have assumed. If it were only one-twentieth of the value assumed, the first rush of current might be explained. The subsequent oscillations superimposed on the current are not, however, explained. They may be caused by the jerk on the oscillograph needle, as suggested by Mr. Worrall, but I do not think so, as the natural vibrations of the oscillograph, damped as they were, would have died out much sooner than the ripples appearing on Fig. 8. It may be that these ripples are due to harmonics in the E.M.F. generated by the peculiar distribution of eddy currents in the pole-face. The pole-face will have in it more or less localised bands of very heavy eddy current corresponding to the very heavy rushes of current which flow initially in different phases of the winding. It seems just possible that these local eddy currents might set up ripples in the E.M.F. generated by the machine. This explanation would be in line with the view expressed by Dr. Sumpner.

Mr. Field has pointed out an apparent disagreement between the figures given on page 296 and those given on page 299. It must be remembered that the resistance r_1 on page 299 is more than the measured resistance of one phase. Just as in a transformer the primary behaves as if the resistance of the secondary (after being multiplied by a certain constant) had been transferred to it, so in this case the resistance and self-induction of all secondary paths affect the operation of the armature circuit. The quantities r_1 and l_1 are the apparent resistance and the coefficient of self-induction of the armature circuit. They have been worked out from the form of the oscillograph curves. I do not agree that any very large fraction of the magnetic energy stored in the field magnet discharges itself on short circuit in destroying the winding. The energy which destroys

Mr. Walker.

the winding is mainly supplied by the kinetic energy of the revolving field. This is proved by the form of the current curves. These show that after $\frac{1}{60}$ of a second the greater part of the magnetic energy still remains as such in the magnetic circuit, whereas we know that the winding is destroyed in the first $\frac{1}{60}$ of a second. The torque on the generator immediately after the short circuit is enormous; the whole armature tends to rotate and shakes the foundations. The apparent change in the frequency in Fig. 5 is due to the change in the speed of the motor which drove the oscillograph strip.

In reply to Mr. Cramp, an increase in the self-induction of the armature will reduce the rush of current on short circuit and an increase in the frequency will also reduce it, because the height to which the current rises depends upon the time allowed for it to rise during the first half-period. In reply to Mr. Worrall, it does not look as though the sudden kicks in the curve in Fig. 8 were due to the undamped movement of the oscillograph, because the kicks do not appear in Fig. 5 where the movement of the mirror was more violent than in Fig. 8, for here the voltage is only 3,900, whereas in Fig. 8 it was 7,000. The effect of a load on the generator at the time of the short circuit will not affect the value of the short-circuit very much, because this depends chiefly on the voltage at the terminals, and the voltage would not be much affected by the load on the machine. I was much interested in Mr. Everest's remarks. I agree that the reluctance of the leakage paths may be very much increased by saturation at great values of the current, and for that reason the short-circuit current may increase more than in proportion to the voltage. Indeed, I think that there is some evidence that this is the case. I also agree that it is the voltage on the machine and not the ampere-turns on the field magnet that is the determining factor. A long air-gap, however, which is generally associated with high ampere-turns on the field, reduces the self-induction of the armature and thus makes the short-circuit current greater.

The President.

The PRESIDENT: We are very fortunate in having had two papers by the same author which have led to so magnificent a discussion. It is really a testimonial to the importance of the subject as well as to the skill with which Mr. Miles Walker has handled it that we have had such an animated and interesting discussion. As a matter of historic interest I might mention that the choke coil which has been proposed by Mr. Partridge was put in the Bristol station sixteen years ago. With regard to another name for "form factor," I would suggest that we adopt the term "crest factor," which would be in accordance with German and French literature. I have now much pleasure in asking you to accord a hearty vote of thanks to Mr. Walker, not only for his very able paper, but for his most interesting reply, which, by itself, is another paper opening up most important vistas of a scientific nature.

The vote of thanks was carried by acclamation.

Proceedings of the Five Hundred and Fifth Ordinary General Meeting of the Institution of Electrical Engineers, held in the Rooms of the Institution of Civil Engineers, Great George Street, Westminster, on Thursday evening, March 17, 1910—Dr. GISBERT KAPP, President, in the chair.

The minutes of the Ordinary General Meeting, held on March 10, 1910, were taken as read, and confirmed.

The list of candidates for election into the Institution was taken as read, and it was ordered that it should be suspended in the Library.

The following list of transfers was announced as having been approved by the Council :—

TRANSFERS.

From the class of Associate Members to that of Members :—

Henley L. Howard. | David Eardley McLaren.

From the class of Associates to that of Members :—

Henry Brazil. | Lucien A. Legros.

From the class of Associates to that of Associate Members :—

John Burns. | Frank Walker.
Ferrand Agnew Williams.

From the class of Students to that of Associate Members :—

Andrew N. Aikman.	Philip V. Hunter.
John Angus Allan.	Harold C. Jenkins.
A. McL. Atkinson.	C. L. J. B. Nadaud.
Emil S. Conradi.	Harold W. T. C. Sabine.
Harry Alex. Edger.	Frank C. Sharp.
John Scear Gibson.	Wm. Whitelegge Thomas.
Ernest J. Harper.	Wm. Bernard Thompson.

The discussion on Mr. Miles Walker's papers was concluded (see page 380), and the meeting adjourned at 9.55 p.m.

Proceedings of the Five Hundred and Sixth Ordinary General Meeting of the Institution of Electrical Engineers, held in the Rooms of the Institution of Civil Engineers, Great George Street, Westminster, on Thursday evening, April 7, 1910—Dr. GISBERT KAPP, President, in the chair.

The minutes of the Ordinary General Meeting, held on March 17, 1910, were taken as read, and confirmed.

Messrs. J. S. S. Cooper and A. P. Haslam were appointed scrutineers of the ballot for the election of new members, and, at the end of the meeting, the following were declared to have been duly elected:—

ELECTIONS.

As Associate Members.

Arthur Angers.
Robert Bruce.
William Stanley Burge.
Cecil Frederick Button.
John Park Chisholm.
John Crane.
William Cruickshank.
Henry Charles Eagar.
Alfred James Eames.
Georges Golliez.
Walter Reynolds Groom.
Hubert Stanley Hohne.
Edward John Morrell.
Samuel Thomas Pemberton.
Charles Henry Phillips.
Albert Richard Powell.
Herbert Skelton.
William Henry Starkey.
John Pattinson Thomas.
Arthur Edwin White.

The following paper was read and discussed: "The Progress of Electric Braking on the Glasgow Corporation Tramway System," by A. Gerrard, Associate Member (see page 390).

The meeting adjourned at 9.48 p.m.

THE PROGRESS OF ELECTRIC BRAKING ON THE GLASGOW CORPORATION TRAMWAY SYSTEM.

By A. GERRARD, Associate Member.

(*Paper received from the* GLASGOW LOCAL SECTION, *January* 13, *read in London on April* 7, *and at Glasgow on April* 12, 1910.)

There are many points in connection with the operation of electric tramway cars which are of interest, not only to the management of the undertaking, but also to the general public. However, there is, in the author's opinion, no point of so much interest and importance as that of braking the car. This interest is, unfortunately, kept alive by an occasional car getting out of the motorman's control. It is therefore hoped that this subject will not be out of place at this time. It is usual in a paper such as this to touch upon the history of the subject, so it is proposed to show the progress of braking since 1898, so far as it pertains to the author's experience in connection with the operation of the tramway system belonging to the Corporation of the City of Glasgow. It may be metioned at this stage that all the statistics which it is intended to put before members have been obtained from the tramway undertaking referred to, under the author's personal observation.

Electric street traction was inaugurated in Glasgow in the autumn of 1898, the track from Mitchell Street to Springburn being equipped as an experiment. At that time the electrical equipment on the cars was partly British Thomson-Houston and partly Westinghouse. The controllers were arranged for electric braking, as recommended at that time by these firms.

Rheostatic Brake.—The brake, as arranged by the Westinghouse Company, was what is now known as the rheostatic brake, and was simply a circuit which included the armatures, field coils and rheostat. The rheostat was gradually cut out as the car slowed down until the motors, which were working in parallel, were short-circuited on themselves.

Electromagnetic Disc Brake.—The British Thomson-Houston brake was composed of two sets of discs per car, one set of discs or the brake for one axle comprising one revolving and one stationary disc. These discs were about 22 in. in diameter, and their adjacent faces were machined for rubbing against each other, and setting up friction which assisted in retarding the car. The revolving disc, known as the brake disc, was keyed to the axle, and the stationary or rather non-

revolving disc, known as the brake-shoe, was supported on two lugs projecting from the motor case. The brake-shoe, although prevented from revolving could, when magnetically attracted, travel across the truck and make contact with the brake disc. There were embedded in each brake-shoe two magnet coils, which formed part of the electric brake circuit, so when the brake was applied to a moving car, the shoes became magnetised, and drew themselves into mechanical contact with the revolving brake discs. The car was therefore retarded electrically through the work done by the motors acting as generators, magnetically by the revolving brake disc cutting the field, and mechanically by the adhesion of the machined faces of the brake-shoes to the brake discs. The brake-shoes, being necessarily thick to receive the magnetic coils, were heavy and rather

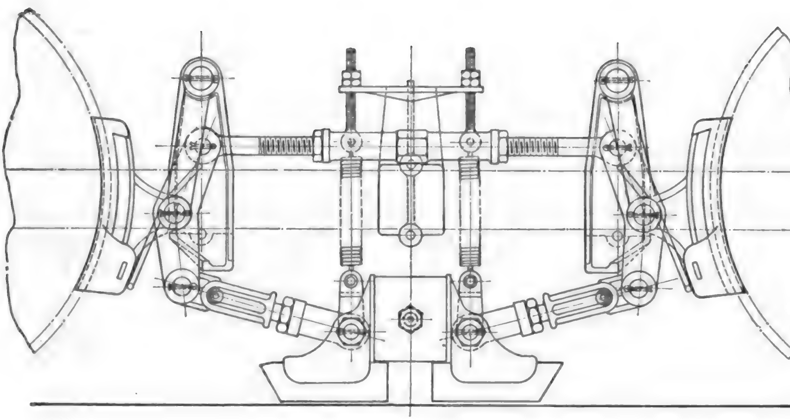


FIG. 1.—Westinghouse Magnetic Brake on Brill Single Truck operated by No. 21 Magnets.

difficult to attract to the revolving brake disc. They were not suspended in any way in order to allow them to move freely, but simply lay on the lugs projecting from the motor case. It will be readily seen that they were of little use for braking the car if the current was light, as, for instance, in coasting * or at the beginning of a service stop. They only did their work when a very heavy current was passing through the equipment, and when they did act, the result was so severe that skidding of the wheels usually took place. The equipment was also complicated, since in starting up on the power side it was necessary to shunt a portion of the trolley current through the magnetic coils of the brake-shoes in the opposite direction, in order to demagnetise them and allow the car to accelerate. Ten

* *Coasting* by means of the electric brake means that the controller handle is set on the first, second, or third braking-point, according to the gradient, and the brake is then allowed to take care of the car.

years have passed since this type of brake was used in Glasgow, so I am unable to say more about them, as they were removed from all the cars thus equipped, which were then simply connected up for rheostatic braking.

Electromagnetic Track and Wheel Brake.—About this time, 1899 and 1900, Mr. F. C. Newell, an American railway engineer, invented and patented what is known as the Newell brake. The design of this braking apparatus is very ingenious, and was a great stride in the right direction. Fig. 1 shows this brake fitted to an ordinary four-wheel Brill single truck. The component parts of this brake are :—

1. Two powerful electromagnets, one suspended over each rail. To each magnet is fitted two mild steel track-shoes, one to each pole. The magnetic circuit is completed through the core of the electromagnet, the track-shoes and the rail, while the coils of the electromagnets are energised by current from the motors when acting as generators. The two magnets are connected in parallel, so that all the current which is generated by the motors is equally divided between them (Fig. 19).
2. Special wheel-shoes which have no connection with either hand brake-shoes or rigging.
3. Connecting rods and levers between the track magnet and the wheel-shoes, so arranged that any movement of the magnets either forward or backward will apply the wheel-shoes to the wheels.

The track magnets are each suspended from the truck frame by two spiral springs, and their shoes are adjusted to within $\frac{5}{16}$ in. of the rail. The action of the brake is as follows : When it is applied on a moving car, the magnets immediately adhere to the rail and drag, falling behind their normal or central position on the truck. This backward motion or lag is utilised to apply the wheel-shoes through the medium of the connecting rods and levers. The magnets lag behind their normal position until all the slack motion has been taken up, and the wheel-shoes are tightly pressed against the wheels. Thus, with this type of brake there are three powerful agencies at work, all assisting to retard the car :—

(*a*) The electrical work performed by the motors acting as generators.
(*b*) The drag on the rails by the track magnets.
(*c*) The friction set up by the special wheel-shoes.

Leverage.—The leverage exerted on the shoes of the leading wheels is in the ratio of 3·346 to 1, whereas the leverage on the shoes of the trailing wheels is only in the ratio of 2·175 to 1 (see Fig. 2). This unequal division of the leverage is designed to compensate for the unequal distribution of weight between the leading and trailing wheels

when a fast stop is being made, or even when stopping slowly on an incline; for it will readily be seen that when a fast stop is being made, or when coasting down an incline, very much more than half the weight of the car is thrown upon the leading wheels, so a greater leverage can safely be applied to them without fear of skidding than can be applied to the trailing wheels, which are carrying less than half the weight of the car.

In the spring of 1901 the Glasgow Corporation Tramway Department equipped six cars with this type of brake. Some rough tests were then made to find out what it could do. The officials of that time bestowed most of their attention on the capabilities of the brake to make quick stops, and did not pay so much attention to the electrical work thrown upon the motors as has been done of late. However,

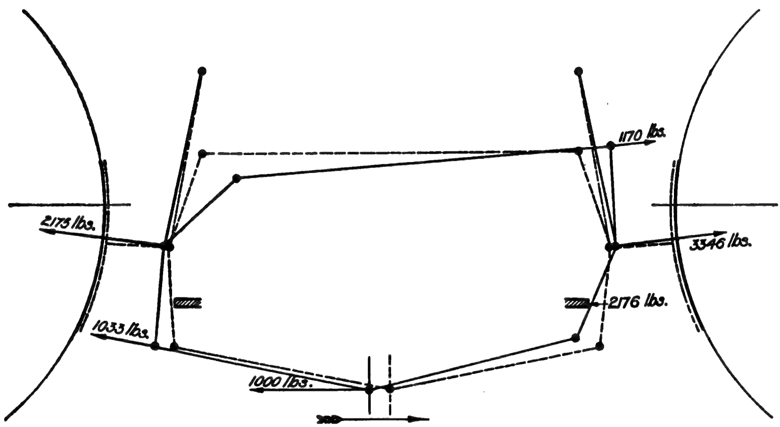


FIG. 2.—Westinghouse Magnetic Brake.

(Diagram of leverage for Brill single truck.)

they were satisfied that the motors were required to do very much less work than in braking through the rheostat only, and the risk of skidding the wheels was thereby reduced. So pleased were they with the performance of the brake that within a very short time every passenger car on the system was equipped with the apparatus.

Damage to Equipment.—The brake question then lay dormant for some time, until the Corporation began to discuss the probable cause of the damage to some of the armatures, controllers, etc. The consensus of opinion was that the use or abuse of the electric brake was responsible for the bulk of the damage referred to, and they accordingly endeavoured to prove this contention. A few rough tests were therefore made to find out the voltage across the armature terminals when the brake was applied, and it was found that when running at 18 to 20 miles per hour

with 10 ohms in the brake circuit, the voltage was as high as 1,000 to 1,200. Those figures were taken roughly, but were in themselves quite sufficient evidence that some alteration would require to be made in order to prolong the life of the equipments. It may be mentioned here that the motors are built to operate at 600 volts maximum, so they could scarcely be expected to generate heavy currents at double that voltage without being damaged and occasionally burned out.

Skidding.—Another interesting point was demonstrated by these rough tests, viz., that 17 to 18 miles per hour was the critical speed at which skidding took place, that is to say, with an equipment such as is installed in Glasgow (namely cars weighing 10 to 11 tons unloaded, equipped with Westinghouse 49B motors, and a resistance of 10 ohms in circuit with first braking-point), momentary skidding took place when the brake was applied even on a level clean rail. It was therefore quite evident, both from a braking point of view and from a desire to protect the equipment, that the voltage should be reduced. It is well to point out that skidding the wheels by the hand brake differs from skidding by the electric brake. If the wheels are skidded by the hand brake they do not revolve again until the brake-shoes are released; therefore to skid wheels by the hand brake means to skid continuously. It is, however, impossible to skid wheels continuously by the action of the electric brake, as immediately the wheels cease to revolve the current dies away, and they are free to revolve again until such time as the current generated by the machines is sufficiently heavy again to cause skidding. Skidding by means of the electric brake can only be intermittent, but if the speed of the car be high enough, the movement of the wheels between the skids will be so slight as to be almost imperceptible. On considering the various ways of reducing the high voltage, it was decided to weaken the field by introducing a shunt resistance in parallel.

Solenoid Controlled Fields.—In January, 1908, experimenting was begun with a permanent shunt resistance in parallel with the fields when braking, but that idea had to be abandoned, because when a low resistance, such as 0·25 ohm, was inserted in the shunt circuit, the motors would not excite, while on the value of the shunt resistance being increased to 0·5 ohm, the braking effect was improved and the voltage kept low, but the machines would not excite quickly enough for an emergency stop. The next move was to introduce the shunt automatically, as required, by means of a solenoid operated switch. This turned out to be the proper course to follow. A brief description of the author's initial experiences with the solenoid control apparatus may perhaps be of interest. He started with the solenoid operated by a shunt coil, and connected the coil across the terminals of one of the armatures. At first the solenoid had a lift of 2 in. When its armature rose, it closed a circuit which was in parallel with the fields, and in which there was inserted a low resistance (Fig. 3). This operated, but not with entire satisfaction, and it was soon found that the time lag between the exciting of the machines and the closing of the shunt circuit was too great. This

time lag must be very small, otherwise the shunting arrangement is of no use, as the voltage rise occurs before the solenoid operates. So the coil of the solenoid was gradually weakened, and the lift of its armature reduced, until it was finally determined that the lift should not exceed $\frac{7}{16}$ in. The next point to decide was whether the coil operating the solenoid should be in shunt to an armature or in series with the main brake circuit. After very exhaustive tests, it was conclusively proved that the series coil in the main brake circuit was the more reliable and instantaneous in action; and it also had the advantage of keeping the armature of the series operated solenoid switch in contact until the car actually came to rest, and the current

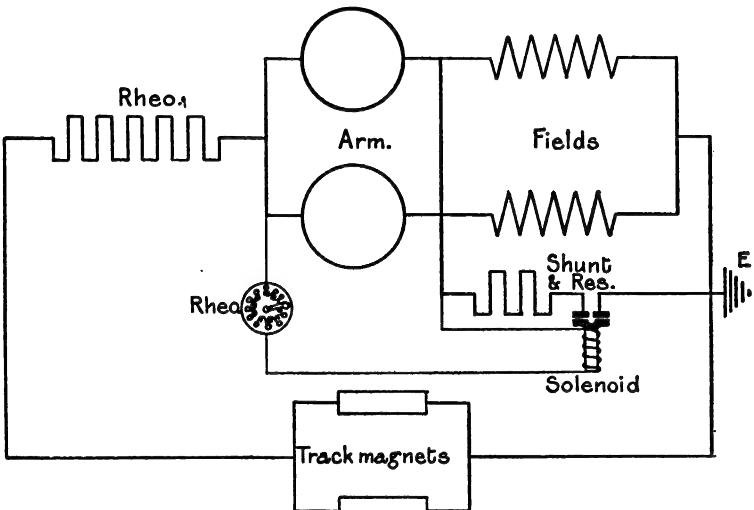


FIG. 3.—Connections for Westinghouse Brake, with Shunt controlled by a Solenoid, operated by a Shunt Coil.

flowing through the circuit had almost died away, so that when the plunger dropped and opened the shunted circuit of the fields, there was practically no arc. In the case of the shunt-operated solenoid, whenever the voltage began to fall, the solenoid dropped its plunger while there was still a comparatively heavy current passing across the solenoid switch. (For diagram of series operated solenoid connections see Fig. 4.) The next two points to be decided were at what current the solenoid should operate and the value of the shunt resistance. After very exhaustive experimenting it was found that when the solenoid operated with 30 amperes and brought in a shunt resistance of 0·2 ohm we had complete control of the voltage, at least up to 20 miles per hour, without impairing the effect of the brake. The voltage never rose above 600, and, of course, there was no

skidding. The next question to be considered was whether this shunt arrangement with the solenoid operating at a comparatively low current would save the motors and prevent skidding in an extreme case of high speed, such as might occur if a motorman at the top of a gradient unskilfully applied the hand brake, thereby skidding the wheels and allowing the car to attain a speed of 25 to 30 miles per hour, and then realised that the proper course to adopt was to release the hand brake and apply the electric brake. As it was not convenient or advisable to carry out tests at those high speeds on the public highway, it was deemed wise to make the solenoid double barrelled (Fig. 5).

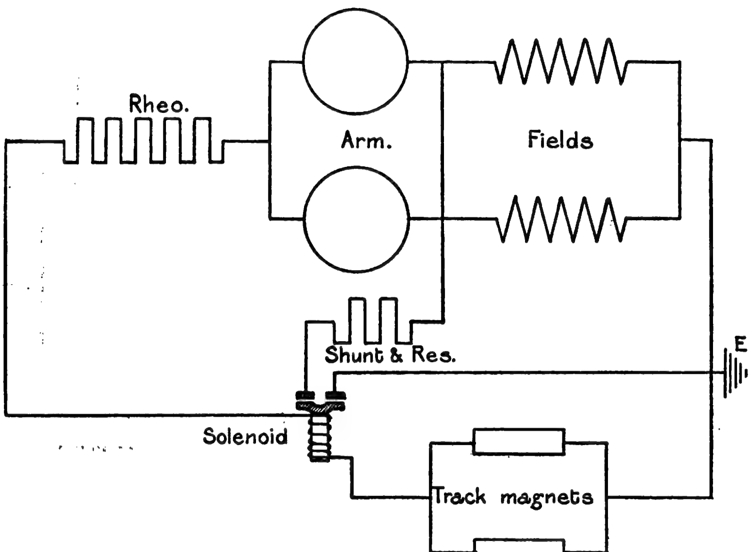


FIG. 4.—Connections for Westinghouse Brake, with Shunt controlled by a Solenoid, operated by a Series Coil.

The low-speed solenoid operated at 30 amperes, bringing in a shunt resistance of 0·2 ohm, and the high-speed solenoid at 80 amperes, bringing in another shunt resistance of 0·2 ohm in parallel with the first (Fig. 6). In the event of a motorman running his car at, say, 18 miles per hour, and, through excitement or carelessness, passing over the first on to the second brake-point of his controller, both solenoids will operate, and thereby bring a shunt resistance of 0·1 ohm in parallel with the fields. This gives the very best results without skidding. It may be mentioned that with this double solenoid control the voltage never rises above 600, no matter what the speed may be.

Track Magnets (*New Design*).—In order that the very best braking results might be obtained in conjunction with solenoid control, two

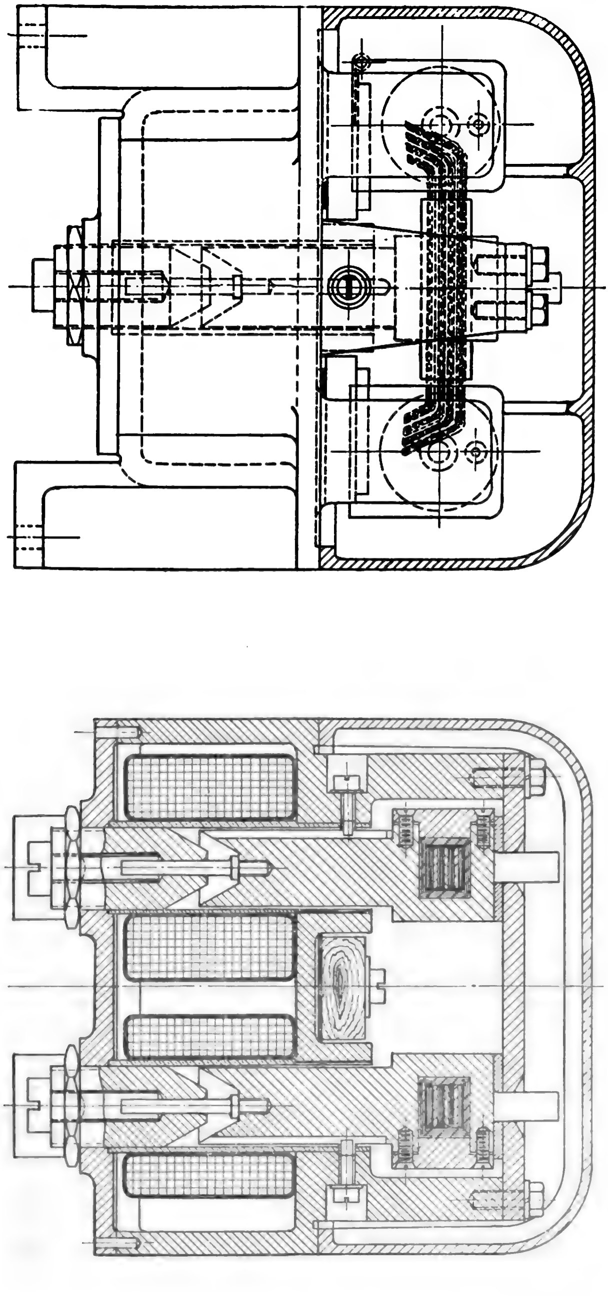


FIG. 5.—Westinghouse Brake Skid-proof Device.

sets of more powerful track magnets were tested. They are listed by the Westinghouse Company as 26C and 25B magnets. The curve sheet in Fig. 7 shows the relative vertical pull of these magnets in lbs.

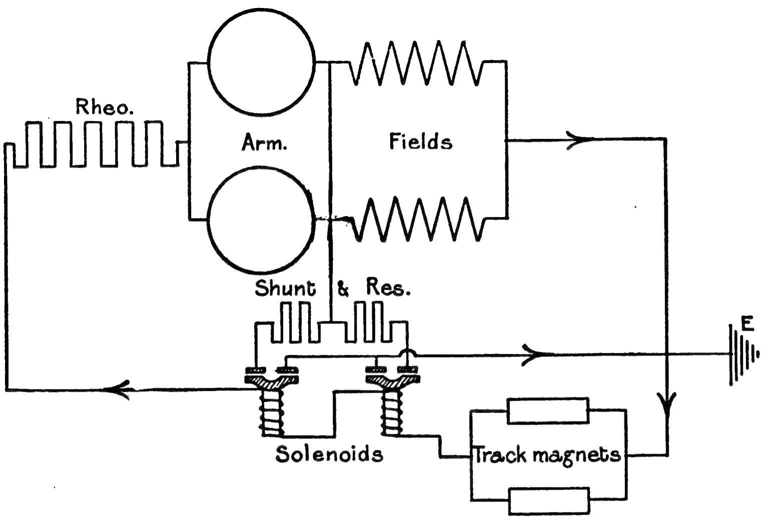


FIG. 6.—Connections for Westinghouse Brake, with Double Shunt, each controlled by a Solenoid, operated by a Series Coil.

weight, as against the old Newell type known as the Standard 21 magnet. The following tabulated list gives the vertical pull in lbs. weight at 5, 10, 25, and 50 amperes:—

VERTICAL PULL OF DIFFERENT MAGNETS.

Type of Magnet.	Exciting Current in Amperes.			
	5.	10.	25.	50.
	Lbs. Weight.	Lbs. Weight.	Lbs. Weight.	Lbs. Weight.
Standard 21	1,050	1,300	1,600	1,800
„ 26C ...	2,400	3,250	3,900	4,100
„ 25B ...	1,900	3,550	4,600	5,150

These new magnets are quite different in design from the old Newell magnet, on which the poles follow each other in series on the rail. On the new type the poles are placed side by side and

parallel to each other. Fig. 8 represents the new standard 26c magnet The 25B is similar in design, only larger. The invention of the new type of magnet marks a most important advance in electric braking, for not only does it give a far greater maximum pull, but its effect with

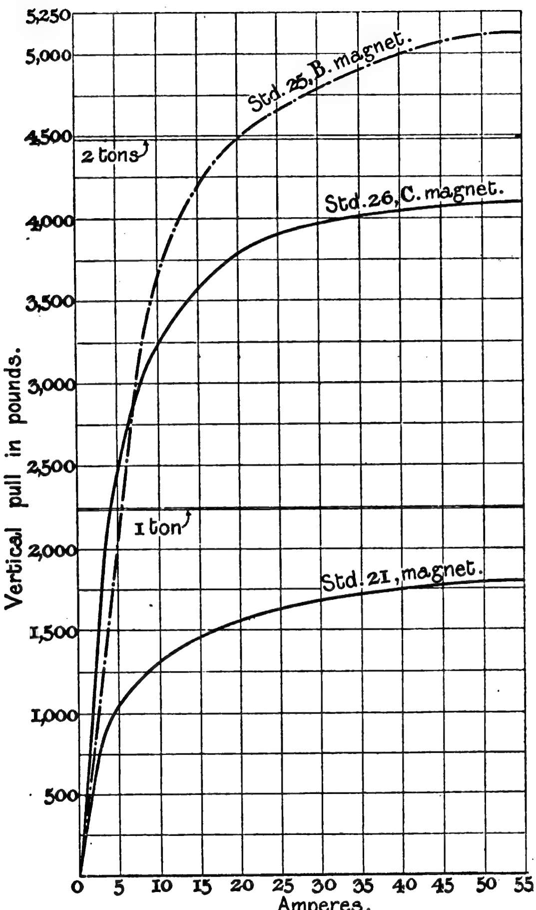


FIG. 7.—Westinghouse Magnetic Brake Curve showing Vertical Pull of various Magnets on Rail.

a current of 5 amperes is greater than that of the old magnet with 50 amperes. The difference in the heating of the motor is most important.

The preceding remarks have been of a general nature, and no detailed figures regarding braking have been given, but data will now

be given which were obtained from actual tests on the tramway track, showing the action of the various track magnets when controlling a car on a gradient unassisted by any wheel-shoe combination, also their action when combined with wheel-shoes and with auxiliary track-shoes.

Coasting.—For coasting tests two gradients were chosen, one 200 yards long, with an average fall of 1 in 27 being selected as the easy

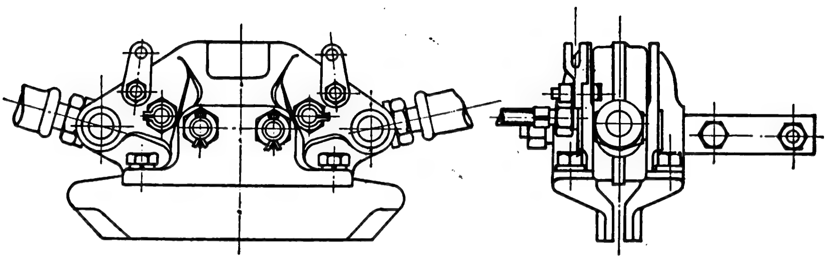


FIG. 8.—Westinghouse No. 26c Magnet.

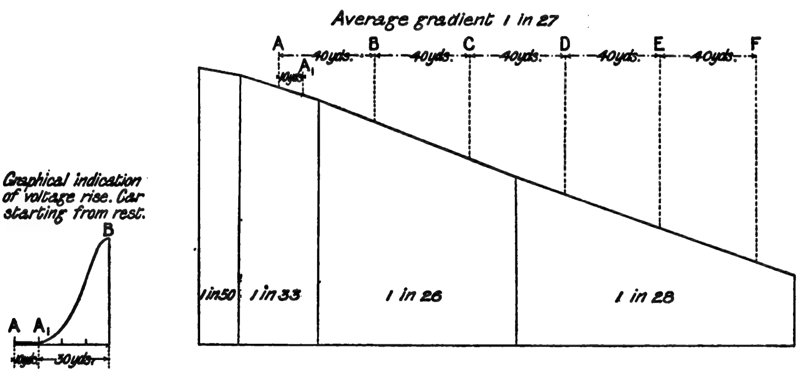


FIG. 9.—Longitudinal Section of Easy Gradient for Coasting Tests.

Point A is where car was started from rest.
" A_1 is where voltmeter indicated excitation of motors.
" B is where maximum voltage was indicated.
" C, D, and E are principal graph lines.
" F is where test was finished.

gradient, while the heavy gradient was 100 yards long, with an average fall of 1 in 13. Regarding the system of obtaining the readings for the curves, the following method was adopted for the easy gradient test. The test ground 200 yards long was plotted off in lengths of 10 yards, with a distinctive mark every 40 yards. The 40-yard marks were known as the graph lines. As will be seen from Fig. 9 (longitudinal section of gradient), the starting-point was approximately 40 yards behind the first graph line. The car, in every test, was started from

rest with the controller set on the second braking-point. The starting-point was arranged so that the first peak or maximum reading coincided with the first graph line. The time in seconds taken by the car to travel over the test ground was checked by a stop watch. The attendants recorded every movement of the instruments, both maximum and minimum. They also took a special reading as the car crossed the graph lines, indicating whether the current was rising or falling. Direct-reading instruments were used. In addition to this, a rough chart was drawn as the car was travelling, indicating the formation of the curve. With the aid of these rough charts and the readings,

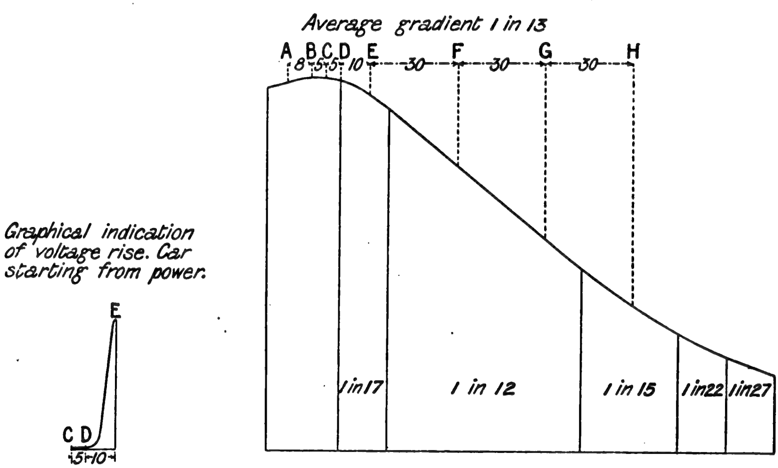


FIG. 10.—Longitudinal Section of Heavy Gradient for Coasting Tests.

Point A is where car was started from, by power.
„ B is where power was switched off.
„ C is where brake was applied.
„ D is where voltmeter indicated excitation of motors.
„ E is where maximum voltage was indicated.
„ F and G are principal graph lines.
„ H is where test finished.

(All distances are in yards.)

curves were formed which, if not strictly correct, are near enough to indicate the values of the various magnets, and of the different brake combinations. On the heavy gradient the test ground was again plotted off in lengths of 10 yards, bu the distinctive marks or graph lines in this case were every 30 yards, the first one being 10 yards from the top of incline. In order that the first maximum reading should approximately coincide with the first graph line, the car, during these tests, was started by power from point A, which was over the crest of the hill from the test ground. At point B, on the very crest of the hill, power was switched off, and at point C the brake was applied on the third braking-point. (For the position of points A, B, C, see Fig. 10

—longitudinal section of gradient.) All other observations were taken in the same manner as those on the easy gradient tests.

In the coasting tests, the general plan was to run first with the rheostatic brake only, and to use the values so obtained as standards to which the values obtained from the other tests could be compared. The following tests were made :—

Test A.—Easy gradient	Rheostatic brake, car No. 438. No. 21 magnet without wheel-shoe attachment, car No. 438. No. 26C magnet without wheel-shoe attachment, car No. 438. No. 25B magnet without wheel-shoe attachment, car No. 438.
Test B.—Heavy gradient.	Same as for Test A.
Test C.—Easy gradient	Newell brake with No. 21 magnet, car No. 368. Newell brake with No. 26C magnet, car No. 687. Newell brake with No. 25B magnet, car No. 438. 1908 brake with No. 25B magnet, car No. 782.
Test D.—Heavy gradient.	Same as for Test C.
Test E.—Heavy gradient.	With and without solenoid control, car No. 438.

In Tests A and B car No. 438 was used. It is a top-covered car with 17 ft. body, and seating accommodation for sixty-two passengers. During these tests a drag chain was fixed between each magnet and the truck in such a way as to permit the magnet to move towards the rail, but to prevent it from operating the wheel brake.

Test A.—It will be seen from Test Table I. and the curve sheet in Fig. 11 that the average current required to control the car on the easy gradient is as follows :—

COASTING TEST.—EASY GRADIENT, RHEOSTATIC *versus* TRACK BRAKE ONLY.

Type of Brake.	Amperes.	Percentage.	Per Cent. Decrease.
Rheostatic only ...	36·72	100·00	—
Standard 21 magnet ...	23·66	64·43	35·57
Standard 26C magnet ...	8·94	24·34	75·66
Standard 25B magnet...	8·00	21·78	78·22

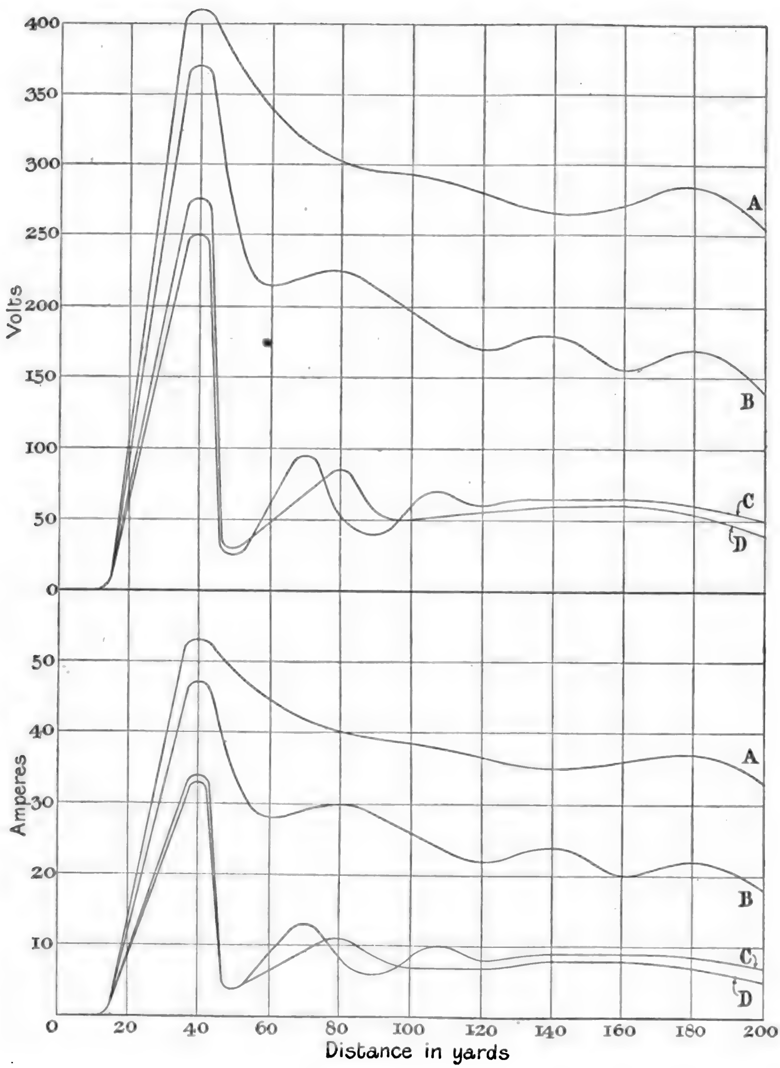


FIG. 11.—Coasting on Track Magnets only.
(Easy Gradient: Average Fall, 1 in 27.)

TEST A.

A	Car No. 438.	Coasting on rheostat only.	
B	Car No. 438.	Coasting on rheostat and track magnets.	Standard No. 21.
C	Car No. 438.	Coasting on rheostat and track magnets.	Standard No. 26C.
D	Car No. 438.	Coasting on rheostat and track magnets.	Standard No. 25B.

In the above test the 25B magnet was slightly superior to the 26C. It may be mentioned here that in calculating the average amperes and volts, the readings from the initial surge are always neglected.

Test B.—It will be seen from Test Table I. and curve sheet, Fig. 12, that the average current required to control the car on this gradient is as follows :—

COASTING TEST.—HEAVY GRADIENT, RHEOSTATIC *versus* TRACK BRAKE ONLY.

Type of Brake.	Amperes.	Percentage.	Per Cent. Decrease.
Rheostatic only... ...	63·27	100·00	—
Standard 21 magnet ...	49·66	78·48	21·5
Standard 26C magnet ...	34·25	54·00	46·0
Standard 25B magnet ...	25·25	39·90	60·1

During this test the 25B magnet again gives the best results, but later on it will be seen that when the combination wheel-shoes are doing their share of the work, and the current passing through the equipment is thereby reduced, the 25B magnet must share the honour with the 26C, which is the more efficient when the current is low.

Coasting Tests on Combination Track and Wheel Brakes.—As it was impossible to test all the various combinations on one car, three other cars appear on the test tables along with car No. 438, namely, Nos. 368, 687, and 782. The bodies and electrical equipment of the four cars are similar. Their rheostats were all set alike, so that the value of R_2 and R_3, the braking-points while coasting, were respectively 6·8 and 3·8 ohms.

Brake-gear.—The brake-gear fitted to the different cars was the following :—

Car No. 368, mounted on an ordinary Brill single truck with steel-tyred wheels was equipped with the Newell brake-gear operated by the old standard 21 magnets (Fig. 1).

Car No. 687, mounted on an ordinary Brill single truck with steel-tyred wheels, was equipped with the Newell brake-gear, operated by the new standard 26C magnets (Fig. 13).

Car No. 438, mounted on a Mountain and Gibson radial axle truck was equipped with the Newell brake-gear, operated by the new standard 25B magnets, the brake rigging being designed to operate the hand-brake shoes.

Car No. 782, mounted on an ordinary Brill single truck with steel-tyred wheels, was equipped with a different type of

ACK MAGNETS (ONLY) AS AGAINST COASTING ON RHEOSTAT (ONLY).

Vestinghouse standard 25B.

ailway bridge.

verage after Initial Surge.		Average of Three Tests.			
mperes.	Volts.	Volts.	Amperes.	Watts.	Watts per Cwt. of Car Weight.
36·33	275·83	279·44	36·72	10,261	44·610
23·43	179·30	181·43	23·66	4,292	18·660
8·83	63·33	63·88	8·94	571	2·480
7·66	58·33	60·83	7·99	486	2·113

y wall on north side of Maxwell Drive.

63·60	296·00	295·66	63·27	18,706	81·330
49·75	240·00	238·33	49·66	11,835	51·460
34·14	164·30	164·80	34·25	5,644	24·540
23·20	112·20	122·93	25·25	3,104	13·500

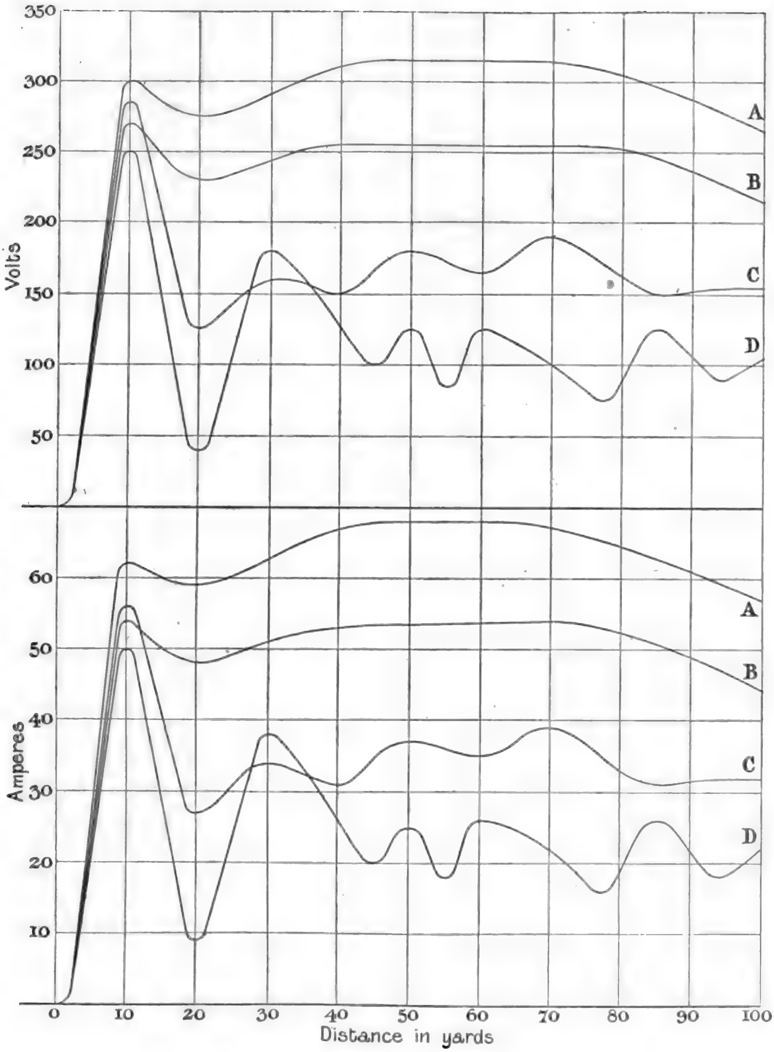


FIG. 12.—Coasting on Track Magnets only.

(Heavy Gradient : Average Fall, 1 in 13.)

TEST B.

A Car No. 438. Coasting on rheostat only.
B Car No. 438. Coasting on rheostat and track magnets. Standard No. 21.
C Car No. 438. Coasting on rheostat and track magnets. Standard No. 26C.
D Car No. 438. Coasting on rheostat and track magnets. Standard No. 25B.

brake, which will be referred to throughout this paper as the 1908 brake. It was placed upon the market during the year 1908. The magnets used were identical with those used on car No. 438—namely, Westinghouse 25B—and the brake rigging was very similar, the only radical difference being

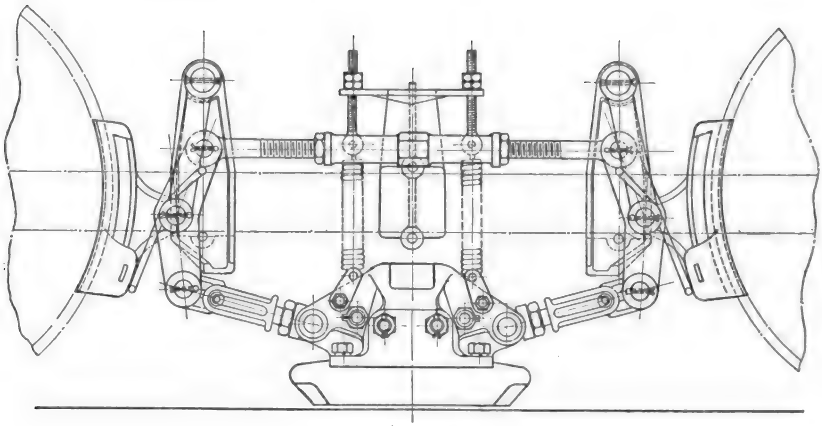


FIG. 13.—Westinghouse Magnetic Brake on Brill Single Truck operated by No. 26C Magnets.

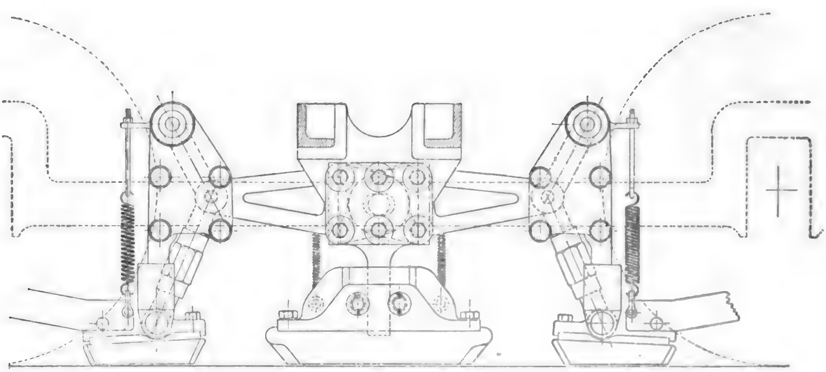


FIG. 14.—"1908" Brake on Brill Single Truck, operated by Westinghouse No. 25B Magnets.

that the motion obtained from the movement of the magnets was utilised in pressing auxiliary track-shoes down on the rail instead of applying auxiliary wheel-shoes (Fig. 14). The idea of substituting auxiliary track-shoes in place of wheel-shoes was to relieve the wheels of the braking effort of the auxiliary wheel-shoes, and thereby reduce the risk of skidding when making fast stops.

Test C: Coasting Tests—Combination Brakes.—On consulting Test Table II. and curve sheet, Fig. 15, we see that the average current required to control the various cars on this gradient was as follows :—

COASTING TEST.—EASY GRADIENT, RHEOSTATIC *versus* COMBINATION BRAKES.

Car No.	Type of Brake.	Amperes.	Per-centage.	Per Cent. Decrease.
Average	Rheostatic only	36·00	100·00	—
368	Newell and Standard, 21 magnet	12·66	35·10	64·90
782	"1908" and Standard, 25B ,,	10·50	29·10	70·90
438	Newell and Standard, 25B ,,	7·44	20·66	79·34
687	Newell and Standard 26C ,,	3·47	9·64	90·36

This test very forcibly illustrates the superiority of the standard 26C magnet when the current is low. By referring to the curve sheet in Fig. 7 it will be seen that when the current falls below 8 amperes per magnet the 26C becomes the most efficient.

Test D.—It will be seen from Test Table II. and the curve sheet in Fig. 16 that the average current required to control the various cars on this gradient was as follows :—

COASTING TEST.—HEAVY GRADIENT, RHEOSTATIC *versus* COMBINATION BRAKES.

Car No.	Type of Brake.	Amperes.	Per-centage.	Per Cent. Decrease.
Average	Rheostatic only	63·00	100·0	—
368	Newell and Standard, 21 magnet	30·10	47·7	52·3
782	"1908" and Standard, 25B ,,	21·00	33·3	66·6
438	Newell and Standard, 25B ,,	13·60	21·6	78·4
687	Newell and Standard, 26C ,,	13·28	21·0	79·0

It will also be seen from the curve sheet that the initial voltage for any of the cars during this test is very low when the nature of the gradient is considered. The reason for this is that after starting with power the machines require less time to excite than after starting from rest without power, as was the case on the easy gradient tests.

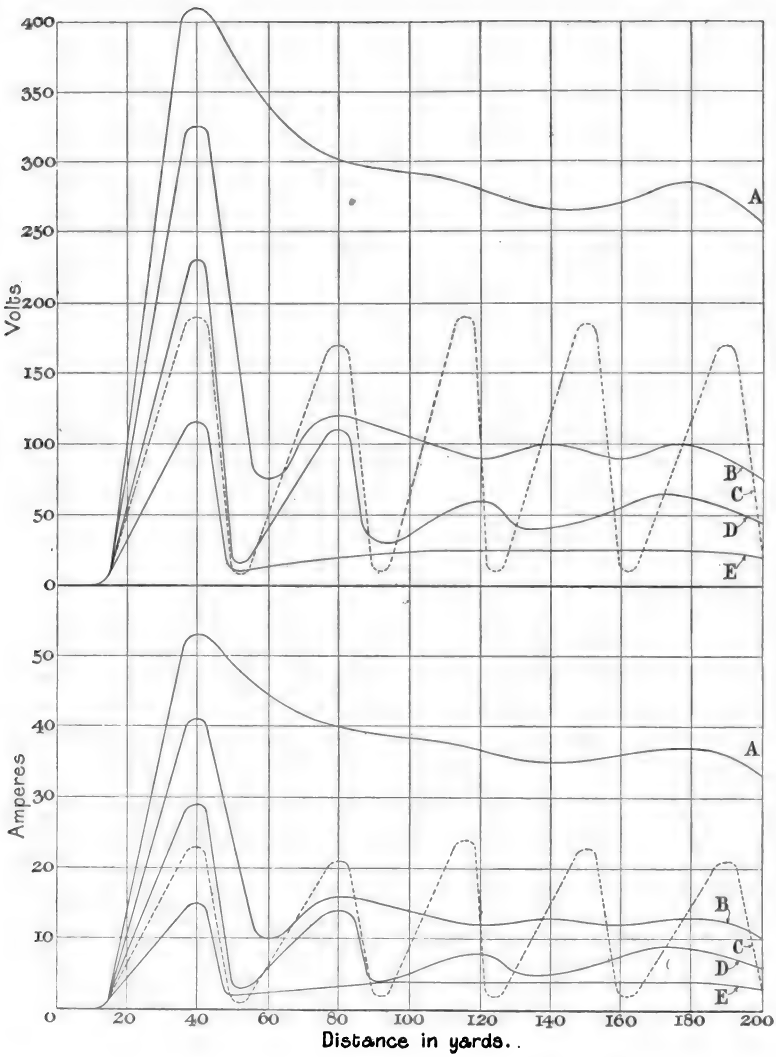


FIG. 15.—Coasting on Combination Brakes.
(Easy Gradient: Average Fall, 1 in 27.)

TEST C.

A	Car No. 438.	Coasting on rheostat only.		
B	Car No. 368.	Coasting on rheostat, track and wheel-shoes.	Magnets.	Standard No. 21.
C	Car No. 782.	Coasting on rheostat, track and track-shoes	Magnets.	Standard No. 25B.
D	Car No. 438.	Coasting on rheostat, track and wheel-shoes.	Magnets.	Standard No. 25B.
E	Car No. 687.	Coasting on rheostat, track and wheel-shoes.	Magnets.	Standard No. 26C.

E COASTING ON COMBINATION TRACK BRAKES.

heel brake. Type of track magnet, standard No. 21.
heel brake. Type of track magnet, standard No. 26C.
liary track-shoes. Type of track magnet, standard No. 25B.
heel brake. Type of track magnet, standard No. 25B.

rage after Initial Surge.		Average of Three Tests.			
peres.	Volts.	Volts.	Amperes.	Watts.	Watts per Cwt. of Car Weight.
·66	95·83	96·10	12·66	1,216·6	5·470
·25	95·63	83·00	10·50	871·5	3·880
·66	58·33	56·10	7·44	417·4	1·810
·40	23·00	24·66	3·47	85·6	0·385
·57	145·70	144·50	30·10	4,348·00	19·500
·33	99·16	97·94	21·00	2,056·70	9·150
·80	57·00	65·83	13·60	895·30	3·888
·15	55·80	61·05	13·28	810·74	3·647

Test E: Coasting under Solenoid Control.—Attention may now be drawn to the beneficial effect of the solenoid control in coasting on the steep gradient where the current occasionally exceeds 30 amperes and so causes the solenoid to operate. On referring to Test Table III. and Fig. 17 we see that under solenoid control the initial surge is checked, the voltage being reduced from 210 to 175, and also that the back-kick is less pronounced, being 25 against 15. The whole reading is more uniform throughout, the number of complete waves being reduced from 8 to 6, the average voltage of the three readings reduced from 82·1 to 65·8, and the amperes from 17·0 to 13·6, while the average time taken to descend the gradient is also reduced from 47⅓ to 46 seconds. By referring to column marked "Current Shunted," Test Table III., it will be seen that in two of the tests the solenoid operated twice, the main braking current having reached or exceeded 30 amperes.

*Surging while Coasting.**—Before leaving the subject of coasting it may be mentioned that great trouble was experienced with surging. The trouble is attributable to various causes—chiefly to the track magnets being too powerful for the weight of the car, to the high leverages between magnets and brake-shoes, and to the track-shoe suspension springs being too strong. Coasting on the rheostat alone is ideal so far as smooth riding is concerned, but it is too costly. A car will coast down an incline on the rheostat as steadily as it will ascend the incline on power, but immediately powerful track magnets are introduced surging more or less will assuredly be set up. Typical examples of surging can be seen by referring to Figs. 15 and 16 (car No. 782) and to Fig. 17 (car No. 438). When car No. 782 was coasting down the steep gradient it was almost brought to a standstill every 10 to 15 yards. The current then died away, and the suspension springs lifted the magnets clear of the track. The car plunged forward again, and so on. Regarding car No. 438, the trouble with it was caused by the powerful magnets operating on a weak truck. The radial-axle truck which was carrying this car body had no stability—that is to say, the magnets through the brake rigging could work the truck out and in like a concertina, and thereby aggravate the surging effect. A good coasting combination can only be obtained with a truck, the wheel base of which cannot be extended or contracted by the leverage of the brake rigging. It is therefore quite evident that on a truck of this kind we cannot have a powerful brake and a perfect coasting brake in one, so a compromise must be arranged. We must put up with the discomfort of a little surging while coasting on heavy gradients in order to have a powerful brake for making fast stops.

Brake Stop Tests.—Brake stops are of two kinds, service and emergency. A service stop is one made by the motorman when he has plenty of time to do so properly, the controller handle being passed

* Surging while coasting means that the car does not run steadily down the incline, but is allowed to accelerate until the brake acts, when it is pulled up almost to a standstill. The brake then releases its hold and allows the car again to accelerate, and so on.

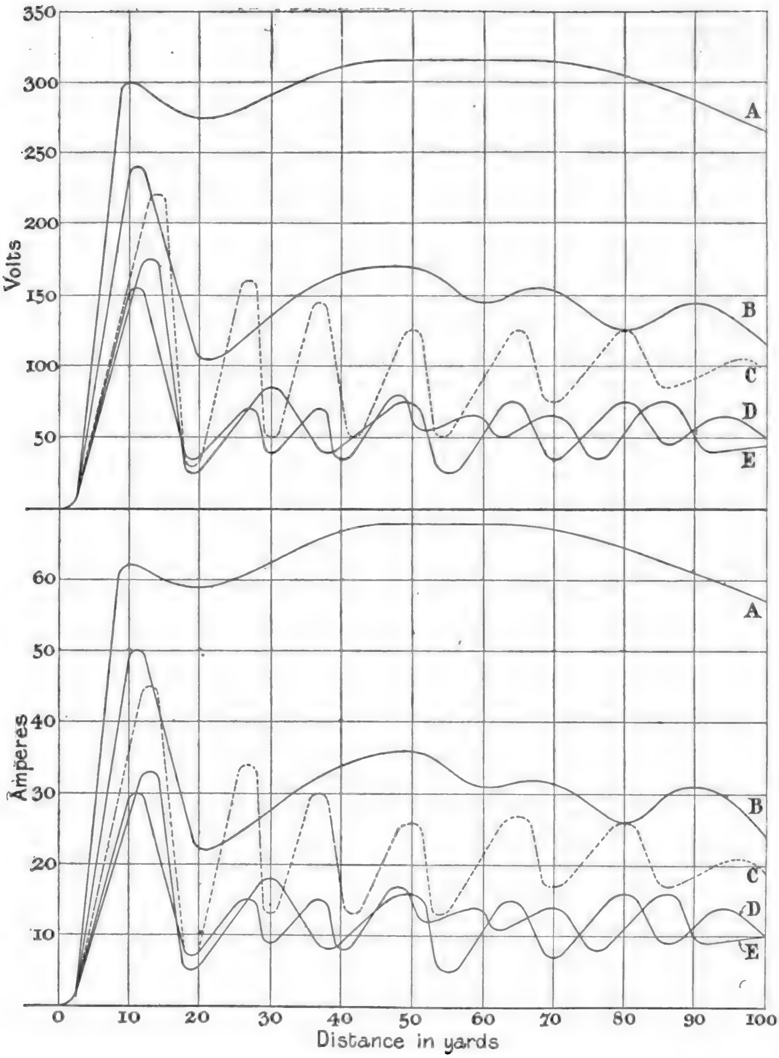


FIG. 16.—Coasting on Combination Brakes.
(Heavy Gradient: Average Fall, 1 in 13.)

TEST D.

A	Car No. 438.	Coasting on rheostat only.		
B	Car No. 368.	Coasting on rheostat, track and wheel-shoes.	Magnets.	Standard No. 21.
C	Car No. 782.	Coasting on rheostat, track and track-shoes.	Magnets.	Standard No. 25B.
D	Car No. 438.	Coasting on rheostat, track and wheel-shoes.	Magnets.	Standard No. 25B.
E	Car No. 687.	Coasting on rheostat, track and wheel-shoes.	Magnets.	Standard No. 26C.

AVY GRADIENT.

tons 10 cwts. 1 qr.

es.

ce = 0·2 ohm,

on north side of Maxwell Drive.

Nature o Start.		Amperes. Average after Initial Surge.	Amperes. Average of Three Readings.	Volts. Average after Initial Surge.	Volts. Average of Three Readings.
From po	5, 20, 5,	19·1	17·03	91·25	82·08
From po	2, 7, 11,	15·4		74·16	
From po	5, 16, 8,	16·6		80·83	
From po	4, 9, 11,	14·0	13·60	68·00	65·83
From po	5, 9, 14,	11·8		57·00	
From po	20, 8,	15·0		72·50	

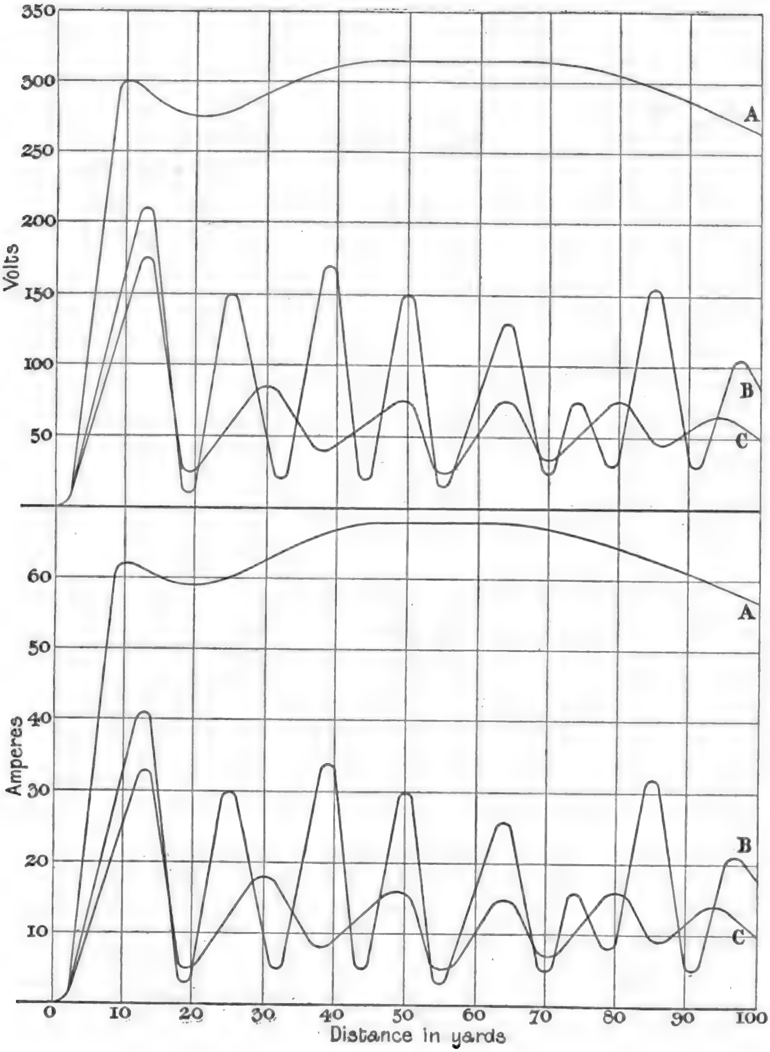


FIG. 17.—Coasting on Combination Brakes, with and without Solenoid Controlled Fields.

(Heavy Gradient : Average Fall, 1 in 13.)

TEST E.

A Car No. 438. Coasting on rheostat only.
B Car No. 438. Coasting on rheostat, track and wheel-shoes. Magnets. Standard No. 25B.
C Car No. 438. Coasting on rheostat, track and wheel-shoes. Magnets. Standard No. 25B.

(With Solenoid Controlled Fields.)

slowly over the braking-points, thereby calling upon the motors to do as little work as possible. An emergency stop is a stop made by the motorman in as little time and in as short a distance as possible irre-

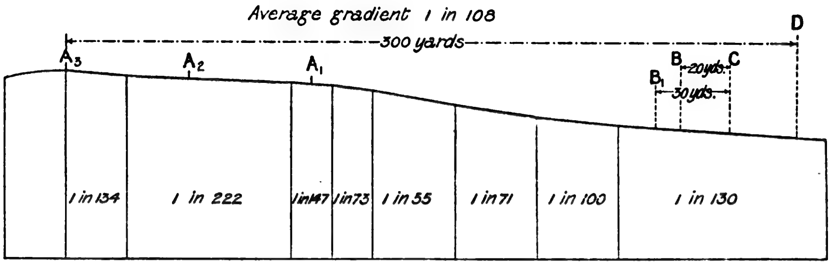


FIG. 18.—Longitudinal Section of Brake Stop Testing Ground.

Point A_1 is where car was started from, in order to attain a speed of 17 miles per hour.
" A_2 is where car was started from, in order to attain a speed of 18 miles per hour.
" A_3 is where car was started from, in order to attain a speed of 19 miles per hour.
" B is where power was switched off.
" C is where brake was applied.

The distance from B_1 to C = 30 yards was used to check speed of car, thus running 10 yards with powers and 20 yards without power.

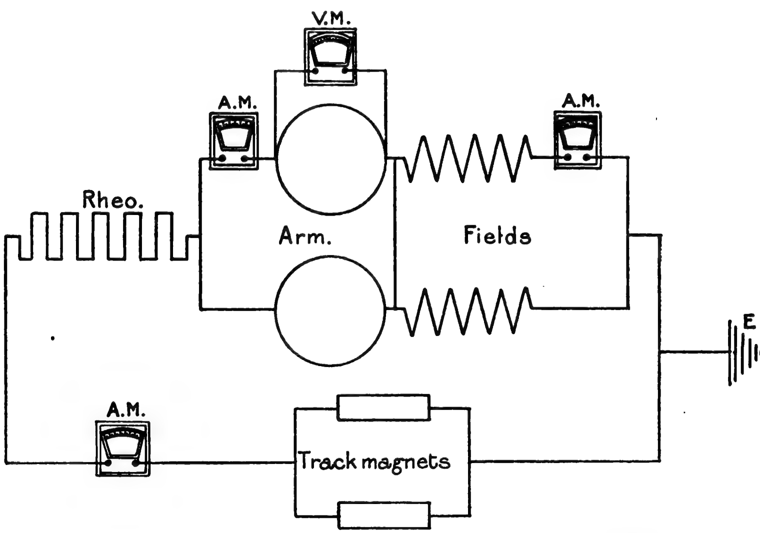


FIG. 19.—Position of Instruments during Brake Stop Tests.

spective of the work the motors are called upon to perform. It was not considered necessary to carry out the brake stop tests at low speeds, so that attention was confined to moderately high speeds, such as 17, 18, and 19 miles per hour. The tests were all made in the daytime on a service track between a car depôt and the main line, on which we

could carry on our work undisturbed. There is an average fall of 1 in 108 on this piece of track. All the tests were carried out in the following manner: For tests at 17 miles per hour the cars were started from point A_1 (see Fig. 18 for longitudinal section of gradient) and run at full speed until point B was reached, where the power was switched off, and then 20 yards further on at point C the brake was applied. For tests at higher speed a fresh starting-point (A_2) was located, from which 18 miles per hour was attained. Then A_3 was located to give 19 miles per hour. Points B and C were never changed. To determine the speed at which the car was travelling when the brake was

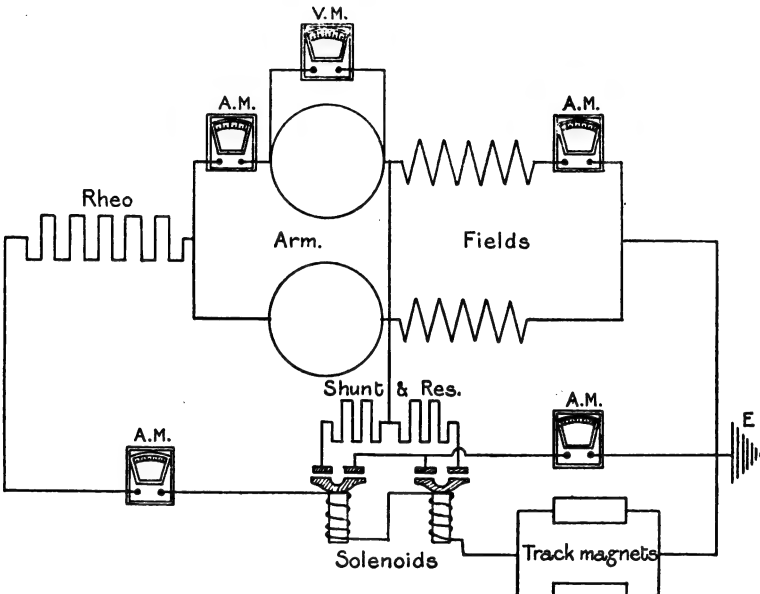


FIG. 20.—Position of Instruments during Brake Stop Tests under Solenoid Control.

applied the following method was adopted. Before the brake was applied the time which the car required to travel over the last 30 yards was checked by stop-watch. Over these 30 yards the car thus ran 10 yards with power and 20 yards without power. (For diagram of connections showing position of instruments during tests see Figs. 19 and 20.) Many preliminary tests were made with various cars and various arrangements of magnets, leverages, and solenoid settings, but it will be sufficient to indicate only the results of the final test between car No. 782, equipped with the 1908 brake-gear, operated by 25B magnets, and car No. 687, equipped with Newell brake-gear, operated by 26C magnets under solenoid control (Figs. 13 and 14). The two cars are alike in general construction and equipment, both

being top-covered cars with 17 ft. bodies and Brill trucks. For full particulars of their equipment see Test Tables IV. and V. It will be seen that car No. 782 weighs 2¼ cwts. more than car No. 687. This is accounted for entirely by the difference in weight of the two brake equipments. The state of the rails when the test began was perfect. In order that the test should be carried out in absolute fairness to both cars so far as the condition of the rail was concerned a special car fitted with emery blocks for grinding out rail corrugations was put on the test track and run up and down for a period of three or four hours immediately before the test was begun, so it may be assumed that the first car on the track had as perfect a rail as the second. Throughout the test no sand was dropped on the rail to assist retardation. On Test Tables IV. and V. will be found the result of brake stops at 17, 18, and 19·176 miles per hour. At each speed three service stops and three or four emergency stops were made. When making service stops at the various speeds, it was our endeavour to make every stop in the same distance—as, for instance, at 17 miles per hour, 60 ft. was the distance aimed at; 18 miles per hour, 70 ft.; and at 19 miles per hour, 85 ft.—in order that we could compare the electrical energy required by the different braking combinations in making similar stops. When making emergency stops, the motorman, of course, pulled up the car in the shortest possible distance. The same motorman and recording staff were engaged throughout the entire test.

Result of Tests.—Test Table IV. shows the results at 17, 18, and 19 miles per hour for car No. 782, and Test Table V. shows those for car No. 687. On comparing the stops at 17 miles per hour we find the following:—

SERVICE STOPS AT 17 MILES PER HOUR.

Car No.	Stop Distance.	Maximum Volts.	Maximum Amperes.
782	60 ft.	875	110
687	57 „	475	70

EMERGENCY STOPS AT 17 MILES PER HOUR.

Car No.	Stop Distance.	Maximum Volts.	Maximum Amperes.
782	34½ ft.	875	190
687	36·0 „	475	140

The emergency stops of car No. 782 at this speed are rather better than those from car No. 687, but at what cost? The last reading from

STOPS.

cwts. 1 qr.

ɔe. Rheostat, Westinghouse 90M type.

ɜs.

Amperes.	Amperes. Average Total.	Remarks.
ɔo, 110, 100	103·0	—
20, 160, 200	160·0	—
40, 180, 160, 180	165·0	—
40, 180, 160, 190	167·5	—
50, (60), 180, 200	177·0	Wheels skidded once
ɔo, (40), 200, 120	140·0	Wheels skidded once
50, (80), 160, (120), 165	162·0	Wheels skidded twice
80, (130), 160, (120), 185	175·0	Wheels skidded once
80, (100), 180, (140), 200	187·0	Wheels skidded once
—	—	At this speed with this car it became impossible to take accurate readings, as the motors flash over and the wheels skid always once and generally twice during every test.
—	—	
—	—	
—	—	

car No. 782 is 33 ft., which works out at a retardation in feet per second per second of 9·44, and when corrected from gradient to level gives 9·69, which is exceptionally high; but, unfortunately, we cannot compare the voltage readings obtained during this test with those obtained from car No. 687 under similar conditions, because the machines flashed over before the voltmeter had time to indicate the true maximum voltage. Turning now to service stops at 18 miles per hour, we find that car No. 782 always skids once, and sometimes twice, during every stop, whereas car No. 687 shows no signs of skidding.

SERVICE STOP AT 18 MILES PER HOUR.

Car No.	Stop Distance.	Maximum Volts.	Maximum Amperes.
782	70½ ft.	1025	200
687	70½ "	525	90

On comparing the emergency stops at this speed, we find car No. 687 making, if anything, the better stops, the last reading, 44 ft., indicates a retardation of 8·18 ft. per second per second, when corrected to level. As regards car No. 782, the only test where the true voltage has been recorded is the first, the 52½ ft. stop, so we might compare the readings taken from it, during this stop, against the readings from car No. 687 during a similar stop.

EMERGENCY STOPS AT 18 MILES PER HOUR.

Car No.	Stop Distance.	Maximum Volts.	Maximum Amperes.
782	52½ ft.	1125	165
687	52½ "	535	150

Brake Stops at 19 *Miles per Hour*.—Regarding the tests at this speed, it became impossible to record the readings for car No. 782, as the first skid always took place before the instrument had time to indicate the true voltage. As will be seen from Test Table IV., the reading taken immediately after the first skid is much higher than the reading preceding the skid. It will also be seen that the voltmeter readings at this speed are very much lower than those recorded at the slower speed tests, thereby proving that the instrument was not recording the true voltage. Altogether, the readings taken from this car at the above speed cannot be taken into account at all. Regarding the stops made by car No. 687 at this speed, both service and emergency, the voltage never rose above 595, and even when making the last two emergency

stops, when the controller handle was passed right over the first braking-point, on to the second, there was absolutely no indication of skidding. When examining Test Table V. there will be found the term "Gradual fall to zero." This means that the instrument (instead of giving a kick every time the controller was moved from one braking-point to another) fell so gradually and uniformly that it was impossible for the attendant to procure intermediate readings. It is not our intention to go closely into the merits and demerits of the two brakes under test, but rather to point out the beneficial influence of solenoid controlled fields; however, in passing a few comments may not be out of place.

Retardation.—Regarding the brake on car No. 782, it has been conclusively proved by our tests that it can bring a car to rest in an extremely short distance, but from observation made during the tests, we are of the opinion that the retardation throughout an emergency stop is the reverse of uniform, being very low at the beginning and extremely high towards the end of a stop—in fact, so high that sitting passengers are hustled along the seats. Retardation to this extent would very soon ruin the framework of a car body, and create no end of claims from injured passengers. What is wanted is uniform retardation throughout the stops. Retardation from car No. 687, in our opinion, was perfectly uniform throughout the most severe emergency stops, being as high at the beginning as at the end of the stop. It will also be seen that it makes very little difference in the voltage whether the controller is properly handled or not, as on every occasion of making emergency stops two tests were carried out, making use of all the braking-points, and other two when the first braking-point was passed over. From the foregoing particulars it seems quite evident that the double solenoid can protect the equipment, and at the same time improve the braking of the car.

Heating due to Braking.—A tramway or railway motor is usually selected with reference to the work it has to do in propelling the car, with little regard to the extra work which is thrown upon it when braking. It is therefore often urged that, since a motor usually operates at a fairly high temperature under normal conditions, the extra load thrown upon it by electric braking is certain to produce more or less rapid deterioration of the insulation. This argument is, undoubtedly, a sound one where rheostatic braking is used, and it may apply also with the earlier types of magnetic brakes, especially if the motor is hard worked under normal service conditions. When the insulation of the motor has been thus weakened, and is subjected to the heavy overloads and excessive voltage which occur in braking at high speeds, there is little wonder that trouble results. But with the latest type of track magnet the current taken from the motors is a very small percentage of that required for rheostatic braking, and when it is remembered that the heating varies as the square of the current, it becomes evident that the increased heating due to braking with this type of magnet is practically nil. If, in addition, the motor fields are provided with solenoid

operated shunts, excessive voltage cannot occur, and the objections to the use of the motors for electric braking have been removed.

Summary.

(*a*) Rheostatic braking is destructive in its action on motors, due to the added heating effect from the high braking currents, and to the excessive voltage generated by the motors acting as generators during service and emergency stops at high speeds. This high voltage causes flashing at the brushes and insulation breakdowns. Rheostatic braking permits smooth coasting, but the current is high, and skidding occurs when braking at high speeds. The retardation is much lower than with the magnetic brake.

(*b*) The Newell brake with the old type of magnet is greatly superior to the rheostatic brake, both in retarding power and in the current consumption, but the current is still high; the voltage generated by the motors during high-speed braking is excessive, and skidding occurs unless the controller is handled with great care. While much easier on the motors than the rheostatic brake, it is severe enough under the best conditions, and when not carefully handled is responsible for a large part of the trouble with motors and controllers.

(*c*) The 1908 brake, with auxiliary rail blocks and parallel shoe magnets, is a powerful one, and requires comparatively little current from the motors, but under the conditions of the tests the voltage rise is excessive, and the skidding serious when braking at high speeds, while the surging during coasting is pronounced. The retardation obtainable is very high but very uneven, probably due to the tendency of the track blocks to grip the rails. The excessive voltage rise might be reduced by means of the solenoid control, but it seems doubtful whether skidding and uneven retardation would be prevented.

(*d*) The Newell brake with parallel shoe-magnets requires little current from the motors, gives good results when coasting, and high retardation under ordinary braking conditions, but the voltage generated by the motors when braking at high speed is excessive, and with emergency stops from high speed, skidding may occur if the controller is not properly handled. This brake is much easier on the motors than the Newell with the old type of magnet, on account of the decreased current required, and for the same reason it is better than the 1908 brake. It would be quite satisfactory were it not for the high voltage and the skidding at high speeds.

(*e*) The Newell brake with parallel shoe-magnets and solenoid controlled shunts to the motor fields possesses all the advantages of the brake described under (*d*), while the possibility of obtaining high voltage on the motors is eliminated and there is no longer any necessity for careful manipulation of the controller to prevent skidding. Exhaustive tests have shown the brake to be skid-proof and the motors to be free from any excessive voltage rise, and it is hoped that actual experience at Glasgow will entirely confirm these tests.

Concluding Remarks.—From actual experience gained, the author is of the opinion that automatic solenoid control of the field, such as has been described, is a valuable addition to the brake-gear of an electric car. It is an everyday occurrence in the life of a tramcar driver to get into a tight corner and have no time to apply his electric brake in the proper manner, notch by notch. Even if he has time, he is sometimes too excited to do so, and passes over the first point or two, with the result that he skids the wheels. He then operates his sand valve, and trusts that the sanded rail will save him from collision. It may be of interest here to point out that the Glasgow Corporation Tramways Department is at present engaged in fitting to each car an automatic sanding apparatus, the component parts of which are a solenoid and a continuous flow sand valve. The coil of the solenoid is inserted in the main braking circuit, and its armature is connected to the continuous flow sand valve, so that, when the solenoid operates, the sand valve is opened, and a copious supply of sand is projected on the rail without any effort from the motorman. A spiral spring is attached to the valve in such a way as to work against the action of the solenoid, and adjusted so that if the electric brake is applied for an ordinary service stop, or for coasting, the solenoid is prevented from opening the valve and serving out sand when it is not required; but in the event of the motorman making an emergency stop, the current flowing through the circuit is sufficient to operate the solenoid and automatically to supply sand at a most opportune moment.

Thanks are due to James Dalrymple, Esq., General Manager, Glasgow Corporation Tramways, for kindly allowing the result of these comparative tests to be put before the members of this Institution, also to the Tramway Department Drawing Office staff and to the staff of the British Westinghouse Company for assisting in the production of these drawings, which have been so useful in illustrating the various apparatus described in the paper.

Discussion.

Mr. Peck.

Mr. J. S. Peck: The interest taken in the question of braking on tramcars seems to be very intimately associated with the number and severity of the accidents which occur. Whenever there is an accident on a tramcar and the investigation shows, as is usually the case, that it is due to some fault in the brakes, the technical papers publish editorials, and the engineering and tramway world in general becomes excited; and when two or three severe accidents follow each other in rapid succession and an investigation is held by the Board of Trade and heavy damages result, then the question becomes one of national interest. The technical and the lay press take it up, and an enormous amount of inventive genius is expended in devising new forms of braking apparatus. For the past twelve or eighteen months there has not been a severe accident, and the question of brakes has been slumbering peacefully. But the fact that we have not had any accidents of late does not mean that accidents will not come, for so

long as defective braking apparatus is used and so long as it is necessary to depend upon the human element for operating the brakes, accidents will continue to occur. Mr. Fell, in his classical paper presented before the Tramway and Light Railways Association in 1906, and in other recent communications, has, I think, shown conclusively that it is possible to obtain a brake which, when properly handled, will give as great a retarding effort as can be reasonably expected. But there has been always the possibility of improper handling, and I think, therefore, that the device described to-night marks a great advance, since it eliminates, as far as possible, the human element, making the braking apparatus practically skid-proof and fool-proof. But another element, which has received scant attention heretofore, is the effect of electric braking upon the rest of the equipment. The author has shown very clearly that, with the rheostatic brake and with the old type of brake magnet, very heavy currents are taken during the braking period, and these currents must add very materially to the heating of the motor, and therefore to the rate of deterioration of the insulation. On page 393, under the heading of "Damage to Equipment," the author sets forth the reasons which led to the investigations and tests, the results of which he has placed before us in this paper. The Glasgow Corporation has long been noted for the extremely low maintenance costs of its tramway equipments, and this is due in large part to the excellent supervision given to those equipments; in fact, I think in hardly another tramway undertaking in the country is such careful attention given to the apparatus. But although their maintenance costs were so low it was decided they were too high, and they began to investigate to try and find out the cause of the trouble. The first thing found was that this heavy current at braking increased the heating in the motors. Then it was found that when braking from high speeds, especially when making emergency stops, the voltage across the armature reached at least twice the normal value. It was probably higher than this, because the voltmeter is hardly rapid enough to measure the instantaneous rise which occurs. With any such voltage as this there will be flashing at the brushes and burning of the commutator, which involves increased attention and reduces the life of commutator and brushes. Moreover, this high voltage tends to break down the insulation of armature and field, and many of the electrical troubles with motors are undoubtedly attributable to this cause. The skid-proof or field shunting device appears to eliminate this excessive voltage entirely. The author tells us they could not get a voltage above 600 even when throwing the controller handle right over to the last braking notch. This seems to be a very valuable point. If Glasgow, having already such a low cost of maintenance, finds it a good commercial proposition to change their old braking equipments for the latest improved type, it may be advisable for all tramway managers to consider following the same course. To me it appears better to take the bull by the horns and recommend the installation of proper braking apparatus

Mr. Peck.

Mr. Peck. than to wait for an accident and then be forced to adopt that course by the Board of Trade, or by indignation on the part of the public.

Mr. Cockshott. Mr. E. H. COCKSHOTT: I was personally associated with the development of the brake referred to in the paper as the "1908" type, and the Leeds Tramway Department, during my connection with it, has devoted a large amount of time to the brake problem, and has conducted an extensive series of experiments on various brakes during the last two or three years. The real name of this "1908" brake is the Maley Electro-magnetic rail brake, of which thirty have been supplied to the Leeds Corporation, and as we have now had a three years' experience of them under actual running condition and on the steepest gradients, we have had numerous opportunities of investigating their general behaviour. We have also in use on our cars many Newell brakes having No. 21 magnets, and have had experience of the latest type of this brake fitted with No. 25 magnets. Our experience teaches us that owing to the excessive voltage and currents generated the sphere of usefulness of the old type of Newell brake is limited to coasting on steep gradients and to making purely emergency stops. The latest type of this brake is undoubtedly a very powerful one under favourable conditions, but at high speeds it became a most difficult matter to prevent the wheels skidding when the brake was applied, and also, contrary to the author's experience, we did not find it satisfactory even at moderate speeds. In fact, so many complaints were received from passengers who had been severely shaken by the irregular and jerky action of the brake that it was decided to remove it. It must not be thought that under all conditions the coupling of the wheel-shoes to the magnets reduces the liability to skid, or limits the current and voltage generated as compared with a magnetic track brake having no wheel-shoes. For a given braking force it certainly reduces the currents and voltage generated if the controller be operated with great care, but should all the resistance be cut out, as generally happens in cases of emergency, it is evident that while the wheels continue to revolve there will be at equal speeds the same maximum voltage and current generated with the two types of brake. The trouble with the Newell brake is, however, that in such cases the wheels having an excessive retarding torque on them commence skidding, and continue to do so for some few seconds, during which time the sudden reduction in the braking force often causes a very considerable increase in speed. In a test made in Leeds with one of these brakes on a gradient averaging 1 in 11 the speed attained previous to applying the brake was 26 miles per hour. On the application of the brake the wheels ceased to revolve, and did not again reach their normal speed until the bottom of the hill was reached, a distance of about 130 yards from the point where skidding commenced. The fact that the car considerably increased in speed immediately after skidding commenced is sufficient evidence of the seriousness of this defect at high speeds. I quite agree that the solenoid device to some extent reduces skidding, but it, nevertheless, seems to me that the addition of such complications into the braking circuit may cause

Mr. Cockshott.

trouble under the rough usage they are likely to get in actual service. I think it would have been more useful if the author had given us the results of trials of the Newell brake and solenoid device at speeds exceeding 20 miles per hour, because at such high speeds it is of the greatest importance that a good brake should be available. With regard to the comparative brake tests made by the author, I feel bound to question some of the figures quoted for the "1908" brake in view of the great number of similar experiments we have made on numerous brakes of this kind, from which very different results were obtained. Taking first Test Table II., the author's figures for the "1908" brake on the 1 in 13 gradient are as follows: Average amperes after initial surge 21·3 and volts 99·16. The figures we have obtained for coasting a much steeper grade, viz., 1 in 9, with a car weighing 11 tons 2 cwts. at 6 to 7 miles per hour, averaged 12 amperes, and the voltage 55 to 70 volts. Taking now the Test Table IV. for service and emergency stops, the maximum figures quoted for current and voltage are 200 amperes and 1,125 respectively. These are indeed somewhat high, but during the whole of the large number of similar tests we have made on this brake, even at speeds up to 28 miles per hour, we have not recorded a voltage exceeding 890 volts. Further, only at speeds exceeding 20 miles per hour have we reached the current value quoted, and even then such a value was only shown by an instantaneous kick of the ammeter. In these references to our experiments on the "1908" brake I am including tests made both on the level and on a 1 in 8·4 gradient with comparative retardations in agreement with those quoted by the author. With reference to the tendency of this brake to cause skidding, it has for some considerable time been claimed for it that the wheels never really skid unless the brake is outrageously misused, and even then it is of such momentary duration that the retardation is unaffected, and throughout our extensive series of trials on this brake in the presence of independent experts it has invariably been observed that skidding was entirely absent. If the wheels did really skid at Glasgow I feel that it can only have been due to the imperfect setting of the brake, and the fact that the generated voltage and current is unusually high and that flashing over has occurred, which we have never experienced in our tests, seems to add colour to this view. In reference to the loads thrown on the motors by the brakes in question, *i.e.*, the "Newell" and the "Maley," it is evident, since the underlying principles are similar, that in each case the braking forces due to the action of the magnets and the auxiliary shoes should, with suitable leverages, be equal, and by separately exciting the magnets and measuring the force required to drag the cars along against the action of the brakes, I have found by actual trial of standard brake equipments that this is practically the case in practice. In view of this, it seems strange that on the Glasgow tests a very much greater wattage is shown when the "Maley" brake was tested than when trials were made on the "Newell" brake. The method of carrying out the tests seems very crude, and one from which the author could hardly expect to obtain reliable figures. It would have been

Mr. Cockshott.

much more satisfactory had recording instruments been used. I cannot agree with the author's remarks in paragraph (c), page 417, regarding the uneven retardation of the "1908" brake, because, provided the rheostat is regulated correctly, our experience goes to show that its working in this respect is all that could be desired. As independent evidence on this point, I might mention that the Tramway and Light Railway Associations Report, in fact, remarks on the delicate graduation of the stops made by this brake. In regard to the summary, it is a peculiar statement which the author makes, that on a "1908" brake it is doubtful whether a solenoid would reduce the tendency to skid or ensure more even retardation. I fail to see why such a device should operate differently with a "1908" brake to the way it does with the Newell brake. There has, however, up to the present been absolutely no need to consider the advisability or otherwise of adding any such device.

Mr. Maley.

Mr. A. W. MALEY: I have felt it necessary to speak, because the paper is largely a comparison of the Westinghouse brake, and the brake of which I am the inventor, the "1908" brake. There are two Brakes Committees, one appointed by the Municipal Tramways Association and the other by the Tramways and Light Railways Association, both of which have been at work on this subject for three years. All the matters referred to in this paper are dealt with in their printed reports, which have been published and widely circulated. I think the chief object of this paper seems to be to make a comparison between the so-called "1908" brake and the Westinghouse brake with the solenoid control. The conclusions arrived at are rather unfair to the "1908" brake, which is giving satisfaction at Leeds and Birmingham. At Leeds in particular they operate over one of the worst gradients in the country, and until they were fitted the Board of Trade would not consent to cars with top deck covers being operated over those gradients. With regard to the tests, generally speaking I think it will be agreed by those who have given much time to the subject, that they are of a very rough character, and consequently somewhat misleading. Very exhaustive tests with accurate recording instruments were made at Leeds on behalf of the Tramways and Light Railways Association by Mr. Fell, the chief officer of the London County Council Tramways. In view of these published tests, extending for over a fortnight, I think the character of the "1908" brake is sufficiently vindicated. The conclusions of the author are at variance with the conclusions of the Brakes Committees' reports. In the first part of the paper emphasis is laid on the fact that the power of the old Westinghouse brake is very small. This can very easily be proved, as Mr. Cockshott has remarked, by connecting the brake with the trolley line, when it will be found that on a very slight gradient if the car is started off at 6 to 8 miles an hour, the brake will barely check the car, that is to say, the generators (the motors, with the brake as used normally) have always done the bulk of the work. I have obtained figures for the old brake, taking drag on magnets roughly at 1,000 lbs., from the leverages shown in Fig. 2, the retardation (assuming 0·25 coefficient

between wheels and rail) on the front pair of wheels would be 836 lbs., and on the rear pair of wheels 543 lbs., or about 2,400 lbs. in all. The retardation, again assuming 0·25 coefficient, of two of the No. 26 magnets giving 8,000 lbs. downward pull, would be 2,000, so that in the newer type of brake the magnets alone are nearly equal to the whole of the brake combination shown in the diagram (Newell old type). One might say, "Why not have a solenoid to control the field in this type of brake?" I think the effect of that would be to restrict the brake to its own power, if the motors are to be prevented from doing the large amount of work they do, and the brake would not then be anything like as powerful as even the ordinary hand brake. It may be of interest to know that this solenoid control was patented by Newell, the inventor of the Westinghouse brake, in 1900 (British Patent No. 9061). It may have been improved in the meantime; I am not very familiar with it. The later Westinghouse brake, with the magnets arranged with the poles side by side, was undoubtedly a great step forward in magnetic braking, but the brake still suffered from the defect that, with powerful magnets, such an extreme thrust was put on the wheels that, although a very powerful brake with rolling wheels, it was liable to cause skidding for a long distance. I have known it in my own experience skid 100 yards; Mr. Cockshott has said he has known it skid 130 yards. That is very serious, because a motorman is absolutely helpless while this is going on. He cannot make the brake let go; he must wait until the residual magnetism of the motors and fields dies down before the wheels will begin to revolve again and give him any effective control. You will no doubt be aware that, when the wheels are skidding, the retarding effect is about one-third of that when the wheels are rolling and being braked to the fullest extent. Those figures are taken from Galton's paper.* As I have already stated, the solenoid control is ten years old, and I do not understand why it has not made more progress in those ten years if it is so excellent an invention, and has apparently given such high results. I refer, in this instance, more particularly to the London County Council system. The tests carried out by Mr. Fell with solenoid control were made about the same time as the tests with my brake, about two years ago. I am subject to correction, but do not think to-day there are many London County Council cars fitted with the solenoid control, although the favourable reports are two years old. Mr. Maley.

On December 16 and 17, 1908, I was in Glasgow, and the "1908" brake was then tested. Mr. Ferguson, the chief Mechanical Engineer of the Glasgow Corporation Tramways, and Mr. Dalrymple, the manager, were present. What I considered successful tests were gone through, and I do not understand why those tests are not included in this report. Provided my memory does not fail me in regard to the dates, another set of tests taken when I was not there, a week later,

* *Proceedings of the Institution of Mechanical Engineers*, 1878, pp. 467 and 490; 1879, p. 170.

Mr. Maley. are mentioned in the paper. In the tests on December 16th and 17th, the stopping distances were rather greater than on the tests on December 22nd and 23rd. The most interesting point was that the stopping distance at 19 miles an hour on December 16th and 17th was 78 ft. I have made a claim which I think will bear examination, that the brake does not skid so as to make any difference to the braking effect. The most we have ever done with our brake is to cause the wheels to stop momentarily, perhaps once, or perhaps twice, but very seldom twice. As it was claimed to be a non-skidding brake, and to be independent of the rail condition, greasy rails should make no difference, and Mr. Gerrard suggested that grease should be put on the rails, which was done, and the same tests were repeated over that grease. The stopping distance then rose from 78 ft. to 90 ft.—a very immaterial increase. This is a confirmation of the tests made by Mr. Fell at Leeds. On the very high-speed stops at about 28 miles an hour, when an official (Lieut.-Colonel Yorke) of the Board of Trade was present, the rails were agreed to be in a very bad state—in fact, there was great difficulty in getting the car back up the hill after the run had been made; under those greasy conditions retardations of 8½ ft. per second were obtained.

Mr. Booth. Mr. W. H. BOOTH: I believe it is generally admitted that electric brakes cause a great deal of injury to equipment, and also by a great many engineers that it is desirable to add some mechanical standby to an electrical brake. I should like to ask the author if a magnetic brake is of any service when the car goes off the line; I think we may answer that question ourselves in the negative. I would further ask if there is any reason why cast-iron brakes, which are very much more efficient in a mechanical brake, should not be used with an electrical brake, and the resistances and coils be designed accordingly? Fig. A shows a mechanical arrangement applied to a drag brake which was tried for some time on the Yorkshire Woollen District tramways. The arrow a' at the head of the diagram shows the direction of the pull which lets down the crosshead p and forces the shoe s upon the rail. The drag then shifts the shoe and tumbler t into the right-hand position, and throws the weight of the car upon the shoe. The arrow a^2 shows the pull of a lever upon the pawl r, which serves to hold down the crosshead p. Fig. B shows a cross-sectional view of the arrangement with a centrally placed tumbler t acting at the middle of a stout transom c. The mechanical pressure is thus equalised upon the two shoes. But usually it would be preferable so to shape the magnetic shoes that each of them might have its own tumbler bearing at the mid-line of the shoe between the magnetic coils. As stated, the gap between the shoe and the rail is $\frac{5}{16}$ in., and the mechanical brake acted extremely well in that position. The only difference was that the brake-shoe was lifted up by rather a stronger spring than usual. When tested electrically or magnetically the spring difference was the only difference made in the equipment, and the car was brought up very quickly, quite as quickly as before this alteration in the spring was

Mr. Booth.

made. The officials, however, who watched the test, observed that the shoe did not come down to the rail, so that the brake acted entirely as a rheostatic brake. Nevertheless the efficiency was very great. It appears from this that magnetic brakes should have very light springs,

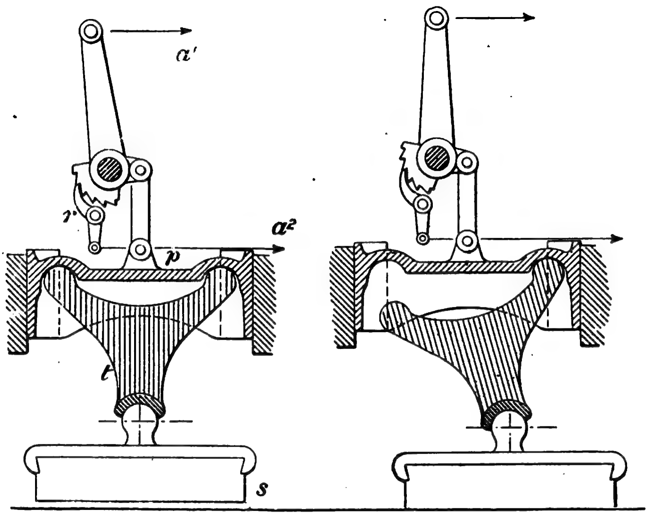


FIG. A.

and there is a tendency for shoes to jar down upon the rail when not in action. I should like to ask the author in regard to Test Table V. how much of the retardation was magnetic and how much of it was rheostatic. Has he any figures bearing upon that point? It would be

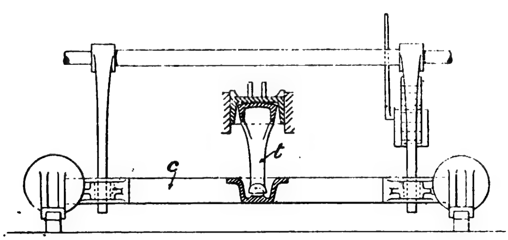


FIG. B.

rather interesting to have these. I take it that the whole of the energy which is used in braking a car by electrical means must come out of the motors, and if so, whichever system is followed, there must be a stress in every case upon the equipment of the car. However useful the electrical brake may be for regular running on light work, it does seem to me that there ought to be some safeguard in the way of a

Mr. Booth. mechanical equipment. The slides shown illustrate one such system, but there are no doubt many other ways by which it can be done. In view of the complications and the possibilities of failure of electrical brakes, why not go back to a brake actuated on the magnetic system, simply from the trolley wire—taking the risk of the trolley coming off and the brake becoming inactive, the mechanical brake being then thrown into action. It seems to me that if we have to face the difficulty of using a mechanical brake—and I think we ought to do so—there is no reason why we should not face the matter boldly by avoiding all the stress on the car equipment, by using the current direct from the trolley line, using the mechanical equipment as a standby, and using it regularly so as to keep it familiar. It may be argued that there is an economy of current in using car momentum to generate the stopping energy, but to me it seems probable that stopping energy can be generated for less cost in fuel and repairs at the big generating station than it can be by the car equipment. The latter method is open to two very serious objections—viz., the driving of the motors through multiplying gears, and the straining of the expensive car axles by the reverse stresses. Car mechanism as now arranged is very crude, and is not calculated to withstand these stresses.

Mr. Sayers. Mr. H. M. SAYERS: I should like to point out the difference in principle between an electrical magnetic brake of the Westinghouse type and mechanical brakes acting either on the wheel or upon the rails. The difference is that with the magnetic brake one can get a retarding effect entirely independent of the available weight of the car. That is not the case with any mechanical brake. In the ordinary wheel brake the amount of retardation that can be obtained is limited by the coefficient of friction between the wheels and rails, and is a function of the weight of the car. With the track brake, whether applied by hand, or by a spring, or air pressure, or in any other fashion, the track-shoes simply take some proportion of the weight of the car, and that is the limit of the retardation that can be obtained by them. Numerically—$32 \cdot 2 \times$ coefficient of friction and fraction of car weight = retardation in feet per second per second. But with the magnetic brake the force available is that of the magnetic attraction between the poles and the rail, and the limit of that is the area of the pole-faces. The maximum attraction that can be obtained with iron of ordinary quality is about 200 lbs. per square inch, so that multiplying 200 lbs. by the pole-faces area in square inches gives the quantity taking the place of the weight in the above expression, and it may exceed the whole car weight if necessary. Of course, there is a limit as regards the comfort of the passengers and as regards the safety of the car structurally, but it is quite impossible by any kind of mechanical brake, whether it is applied to the wheels or to the rails by track blocks, to get anything approaching the 8 to 10 ft. retardation that is available with the magnetic brake. In that respect the magnetic brake represents a great advance. The history of the magnetic brake, as shown by Mr. Gerrard's paper, is a very interesting case of the development of

a crude and destructive device into an economic and useful piece of apparatus. The old pattern Newell brake was shown to me many years ago when I had to deal with tramcars practically, and I declined to have anything to do with it. I said at once it was not a thing that would fit the conditions I had to deal with, and I had too much respect for my motor equipment to put in such a device. The weak point of that was the poor magnetic design of the magnet itself, which called for a very large exciting current in order to get anything like a respectable amount of attraction. The magnet design has now been much improved, so that the amount of current required is not more than 10 or 15 per cent. of that required with the old pattern for the same amount of attraction. The other drawback attached to this brake was the flashing over of the motors when it was used on a car running at a high speed. The author is, I think, the first man to publish the actual figures of the voltages obtained under those conditions, and I think they will astonish people who have not made measurements of that kind. It is certainly not astonishing that tramway motors flashed over, insulation failed, and other damage occurred when they were suddenly subjected to 1,000 or 1,200 volts. In my opinion, the author deserves the thanks of the Institution for having given to it the results of a long series of tests, which must have tried his patience and his observing and recording powers. The making of brake tests is not an easy or a very pleasant matter. On lines in service they have to be made at night, or on Sundays, or some other inconvenient time. The mere mechanical difficulties and discomforts of getting actual records go a long way to entitle the man who does a large amount of work of this kind and then publishes the results to receive the respect and gratitude of his colleagues. I think, with all respect to the opinion of one or two other gentlemen who have spoken, that the paper deals with a very proper electrical subject. The Tramways and Light Railways Association would no doubt have been glad of this paper; speaking as a Member of Council of that Association, I would have been glad to welcome it for publication; but there is not the least reason why this Institution should not have the advantage of hearing it and discussing it. Another feature of brake tests, with which I am sure Mr. Maley is as well acquainted as I am, is that brake tests made in different places and by different people do not give consistent results. I have had to compare and to draw conclusions from a very large number of brake tests carried out by different people at different times and in different places, and I assure you that if one wishes his conclusions from such a set of tests to be respected and given any weight to, he had better publish his conclusions alone and not the tests from which he draws them. The difference between the results of the tests made on Mr. Maley's brake at Leeds by Mr. Fell with a very elaborate set of apparatus for the Tramway and Light Railways Association and the tests made by Mr. Gerrard, as recorded in this paper, show that there must be some essential difference in the conditions which is not revealed by the data given. At Glasgow the brake was evidently Mr. Sayers.

Mr. Sayers. tried under conditions which were unstable—that is to say, the relationship between the motors and the brake windings and the resistances in circuit were such that surging was set up. At Leeds, no doubt, the motors were of a different type, and there were other differences in the circuits which gave steady conditions. I can speak for the Leeds results, because I saw the whole of the original curves, and they showed a uniformly high retardation. I do not think that Mr. Maley's invention should be judged by the results given by Mr. Gerrard, although I am not in the least inclined to think that Mr. Gerrard was consciously or intentionally unfair to the Maley brake. I think that all the results available show that the magnetic type of brake is the best brake there is for conditions requiring frequent stops or high speed under more or less emergency conditions—that it is the best brake not only for heavy tramway traffic conditions, but for heavy general traffic. Under those conditions, such as obtain in London, Leeds, Glasgow, and other large cities, it is of the highest importance that the driver should have power to do almost anything up to just short of destroying his car rather than hit another vehicle or pedestrian. For those conditions I think the magnetic brake is the best thing there is, and with the addition of the solenoid control it becomes very nearly perfect as regards its efficiency and ease of operation. But it is a very complicated device; it adds largely to the complication of the electrical wiring and the controller apparatus, and the addition of these so-called solenoids is another complication. Mr. Fell in his paper * pointed out that the Westinghouse brake has to operate through an electrical circuit, using a very large number of controller contacts. It is not only necessary that the circuit should be intact throughout the whole of the operation, but also that the resistance of the circuit shall be very low, because the motors have to build up through the circuit whatever the resistance is, and a dirty contact, or a loose contact, or a wire loose in the terminal may make all the difference between the motors building up and refusing to build up. Accidents due to this can only be prevented by careful, skilled inspection, and the regular frequent use of the brake tends to detect trouble very quickly. When you come to the question of controlling cars down steep gradients, and where there is no other reason for using such a brake as the Westinghouse, I do not think there is any need for such an expensive and complex apparatus. I notice that the steepest gradient mentioned in the paper is 1 in 13. I have had to provide for something considerably worse. For coasting down a steep gradient it is essential that the car stops at the top of the gradient, and that the track brake is put on before it moves, and that cannot be done with a purely magnetic brake. So that if a magnetic brake is used on lines with such gradients for other reasons there should be added to it means of applying it mechanically at the beginning of the descent. To make it safe it requires just as careful and frequent inspection as if it were used in a busy city

* *Tramways and Light Railways Association, Official Circular*, No. 38, February, 1908; also *Electrical Engineer*, vol. 37, pp. 56, 79, and 124, 1906.

service, and on poor country lines, on which some of these steep gradients occur, that cannot be afforded. Therefore for such lines I remain of the opinion that the mechanically applied track brake is the best thing, and it is a great deal cheaper than the magnetic brake. Mr. Sayers.

Mr. H. E. YERBURY (*communicated*): The efficient braking of tramcars is a most important subject, and recommendations relating thereto were published in 1908 by the Municipal Tramways Association and the Tramway and Light Railway Association. I take it that the author does not suggest that anything new has been introduced in this paper, but that a useful discussion might be brought about as to the application of a solenoid device for controlling motor field current and thus eliminating all danger of skidding car-wheels. It has been amply demonstrated that the rheostatic brake is unsuitable as a service brake, and although there are hundreds in operation at the present moment, the constant application of this brake has a serious effect on the electrical equipment, and it should only be looked upon as an inexpensive yet effective brake for emergency stops. The development of the magnetic track brake apart from the wheel brake-shoes was a step in the right direction, and undoubtedly solenoidal control of the motor fields for the past year or two has given excellent results. It is regrettable that the author has confined his attention to one particular form of brake, instead of giving comparative data concerning other well-known forms of magnetic track brake where auxiliary brake-shoes are pressed down on the rails, but presumably the author desires simply to emphasise the fact that with solenoidal control much less work is put upon the motors, and "locked wheels" which have caused so many serious accidents in the past can now be avoided. Tramway engineers cannot fail to agree with the points set out in the author's summary, and it appears to me that it is only a question of time before brakes in general will be magnetically operated and manual labour will be reduced as much as possible. Mr. Yerbury.

DISCUSSION AT GLASGOW, APRIL 12, 1910.

Mr. JOHN FERGUSON: I wish to confine my remarks to a few words upon electric braking generally. Electric brakes have not been adopted on some systems for various reasons, which are given very fully in the paper. The first is that if the electric brake is applied quickly, especially at high speeds, the tendency is to stop the wheels from revolving and to cause skidding. The second reason is that the frequent use of the brake, especially at high speeds, tends to increase the maintenance cost of the equipment generally, especially of armatures, and it can be readily understood that it has also a serious effect upon the car bodies. The third objection is that the brake depends for its action upon a number of controller contacts which are more or less liable to get out of order; and the fourth is that it can only be applied when the car is in motion. It is therefore impossible to tell if the brake is in order when the car is stationary. These are Mr. Ferguson.

Mr. Ferguson. difficulties which exist in any form of electric brake. I think, however, it will be evident that the introduction of the solenoid control has effectively removed the first two objections; at any rate there can be no doubt that the skidding objection has been removed, and it may be confidently expected that on account of the greatly reduced demand made upon the motors the armature maintenance cost will be materially lessened. We have not had sufficient experience or gone far enough in the direction of solenoid control to tell what the reduced maintenance cost will be, but from the low voltage and current figures given in the paper there can be no question that it will have a very beneficial effect upon the equipments generally. The elimination of skidding is a great step forward. Motormen cannot fail to appreciate the advantage of a brake attachment which enables them, when called upon to make a sudden or emergency stop, to apply the brake to its full capacity at any speed at which they may be running, without incurring any risk of skidding the wheels. The paper, however, does not claim that either the third or fourth objection has been removed. On the whole, however, after seven or more years experience in Glasgow, we have not found that these objections amount to very much. We have ascertained roughly that the average number of times the electric brake is applied in the course of a day, with a car running an average of 120 miles, is just under one application per mile. Roughly speaking, the applications of the electric brake throughout the year amount to eighteen million. The number of reports received during 1909 as to defective electric brakes amounted to 17, and the greater proportion of the number when investigated were found really not to be defects in the brake, but in its application.

Mr. McWhirter. Mr. W. McWhirter: We are very much indebted to the author and to the Glasgow Corporation Tramways Committee for publishing the results of work done, so that the public may obtain the full benefit of the knowledge acquired. Those who attended the meeting of our Institution in Glasgow in 1901 must remember the paper read on "High Speed Electric Railways."* I think that was an epoch-making paper and showed what can be done with a little collaboration. The work was done and the cost was borne by the German Government and three or four of the largest German manufacturing firms. In connection with braking I remember that about thirty years ago the Board of Trade, in conjunction with the chief officials of several of the railways in England, carried out elaborate experiments on the pneumatic brakes then before the public, using various speeds and weights of trains, and the commission issued reports which tramway managers would do well to study most carefully. On page 399 of the paper we get a set of interesting curves giving the vertical pull of three types of magnets used in the experiments. I should have been glad to see a cross-section of those magnets including a surface contact with the rails. Magnet 21 has practically reached saturation with 40 amperes, the pull being 1,750 lbs., or less than double the pull at 5 amperes. The

* *Journal of the Institution of Electrical Engineers*, vol. 31, p. 24, 1902.

Mr. McWhirter.

cross-section of this magnet is obviously much too small for effective work. Magnet 26C shows how the above objection has been removed; the increased core section having more than double the pull. Magnet 25C is on the same lines carried further, and the tests show that the increase in cross-section of the magnet core has been carried too far, as in actual use this magnet, and even 26C, appear to have ample pull while magnetised on the vertical part of the characteristic curve; consequently the tractive effort must be very unstable and surging readily set up. The curves (page 403) show rheostatic braking to be lacking in efficiency and the currents required very heavy. The addition of the track magnets seem to form an ideal braking arrangement, but still the currents are heavy and unnecessarily severe on the motors. The author refers to the enormous rise in voltage when braking at high speed; the maximum speed of the Glasgow cars running on the level is about 16 miles per hour. Why should that rise take place? To my mind it shows that in the design of the motors used on the tramway cars there is a superabundance of iron in the fields. These experiments indicate that in the Glasgow motors the magnetisation at normal load is on the vertical part of the characteristic curve. The matter of braking was not perhaps taken into consideration when the motors were designed, as their primary use was for traction, and of course it is necessary that the field magnets should not be saturated at normal load, in order that full advantage might be got from the heavy currents required on steep grades.

However, the application of the solenoid control removes the objection, and keeps down the rise in voltage at any given speed. I think that is a most admirable arrangement, and will be widely adopted if the cost of the solenoid arrangement is not too heavy. The result would be a great saving in motors, controllers, and the cars generally, and less risk of injury to passengers in consequence of emergency stops. I am sure the author did not mean for one moment that any combination he has shown us has anything to do with the rise of voltage. His experiments, in fact, show that the rise is altogether due to the design of the motor fields. I should be very glad to see a cross-section of the various magnets (cores and poles) he has mentioned in his paper. That of 21 was 6 in., the next is 12 in., and the largest one 16 in. I have never seen the magnets, but I think these figures are about right, assuming the pull to be 160 lbs. to the square inch. The author has given us the results of the tests for stopping quickly at high speeds, but I think that stopping at slow speeds going through traffic is just as essential. It would be interesting to know the distance in which a car travelling at 4 miles an hour could be pulled up. I think Mr. Gerrard has said the last word in electric braking. We should not take the black view often expressed about the dangers of electric braking. The figures Mr. Ferguson gave us should remove that doubt entirely. If he has only had one failure in a million applications, that figure could hardly be reduced with air brakes or any other brakes.

Mr. Maxwell.

Mr. J. M. Scott Maxwell: I entirely agree that we are much indebted to Mr. Gerrard and the Glasgow Corporation for giving us the information in the paper, because the question of brakes is a vexed one. Mr. McWhirter mentioned what seemed to me to be a most important point in connection with braking, that it is as necessary to make tests at slow speeds as it is at speeds of 16 to 18 miles per hour. The electromagnetic brake is essentially an emergency brake, and is only used as such on the Glasgow cars. An electromagnetic brake is not ordinarily used in heavy traffic; for example, going along Argyle Street, and because it is impossible with a hand brake alone to stop a car quickly when going at even a moderate speed, an electromagnetic brake for emergencies must also be installed. The combination of the hand brake and the electromagnetic brake is not a satisfactory one in a city like Glasgow, and as long as we retain this combination we shall always have a slow schedule speed, because the motorman is not allowed to use the electric brake except when a real emergency arises. In place of the present brake combination, air brakes should be used, but the whole question boils down to this, that the Glasgow cars are single-truck cars, and air brakes cannot be fitted for want of room. While discussing the question of double-truck cars some years ago, I understand that Mr. Dalrymple said the Glasgow street cars are such that it is impossible to put on longer cars. It is all a question of turning corners, and I think that some of the Glasgow routes could be changed, as it does not appear necessary to turn so many corners. In America they have double-truck cars which are almost all fitted with air-brake equipments. Now the air brake can be tested when the car is standing still, and the motorman can always see that the air pressure is maintained at all times. It would be interesting to know how many accidents we have had in Glasgow, not at a high speed, but at 4, 6, or 7 miles per hour. It seems to me that these lower speeds are more dangerous than the higher speeds, because with higher speeds people take more care and clear out of the way more quickly.

Communicated: There seems to be some confusion between schedule speed and maximum speed. It is stated that the Board of Trade sets definite speed limits, depending on the traffic conditions. The schedule speed is the speed over the whole route, including all the stops, and it is evident that if the time taken to stop the cars be lessened by means of more powerful and efficient brakes, the schedule speed will thereby be increased without increasing the maximum speed, *i.e.*, without exceeding the maximum legal limit. The very fact that we have more stringent speed limitations in this country than in America is all the more reason why we require more rapid acceleration and stopping. The former requires more powerful motors, the latter more powerful brakes. If we start with the brakes we shall make some advance towards an increased speed. A higher schedule speed means greater carrying capacity. The same number of cars can carry a greater number of passengers, because more trips can be made per

day. This is a better method, therefore, perhaps a cheaper one, to meet increasing traffic than adding to the already large number of slowly moving cars, and thus still more congesting our main streets. Mr. Maxwell.

Mr. A. P. ROBERTSON: I am very much interested in brakes, not only in tramway work, but in other work, such as railway and motor work. On looking at the diagrams, 25B magnetic brake, and 26C magnet, it seems to me that the type illustrated in 25B is not so good for the following reasons. When the brake magnet is excited and grips the rail, the two rail-shoes will be pressed against the rail, and will tend to lift the weight of the car off the wheels. This will reduce the friction between the wheels and the rails, which constitutes the driving force for the armatures of the motors, and they will tend to stop or skid. The excitation will then be taken off the magnet, which will weaken the lifting power, thus allowing the weight of the car to come on the wheels again, and the same cycle of operations will be repeated. The result of this will be a tendency to surge, as shown in the curves for braking effects. I would ask Mr. Gerrard if he found this so, and if this type of brake is still in use. Mr. Robertson.

Professor F. G. BAILY: The surging in the speed of a car when running down a hill is due, doubtless, to a combination of causes. I may suggest as another possible cause that the change of magnetism in the electromagnet lags somewhat behind the change of current. When the speed and current rise the brake delays action, and similarly when speed is reduced by the brake the braking action is prolonged beyond the fall of the current. The same lag will exist in the magnetic circuit of the motors, and the combination of the two will amount to quite an appreciable interval. This will certainly increase the surging, and it may be worth while to consider the interposing of very short air-gaps in the iron circuit of the electromagnet, not only the natural ones at the junction to the rails, but also in the yoke-piece on either side of the bobbin, as is done in Mr. Raworth's magnetic clutch. It would be hardly practicable to apply the same idea to the motors. At a first reading of this paper several criticisms occur to one's mind, but a more complete grasp of the various sides of the problem shows that improvements in one direction usually cause trouble in another. I take it that over-voltage is the difficulty which has brought about the solenoid control. It is obvious that a motor built to give 500 volts at full current, at a speed of 8 miles per hour, will give over 1,200 volts at 20 miles per hour if the full current is allowed to flow through, and the usual starting resistances will not be large enough to control the current under so high a voltage. Hence the necessity for shunting the fields. The control also diminishes skidding, but this could be brought about by arranging a suitable saturation value for the magnet, a simpler plan than the solenoid control. In addition to the voltage regulation, there is the necessity of obtaining full braking at slow speeds, which calls for an easily excited electromagnet. Then comes in the surging and skidding questions if the magnet is too powerful, and these must be checked by strictly limiting the section of iron Professor Baily.

Professor Baily.

in the magnet. I think a magnet with a good deal of leakage will be beneficial in this respect, with uniform cross-section of iron, and the air-gaps above mentioned will assist in this direction. The section may even be slightly throttled before the pole-pieces are reached. Such a magnet will give a tractive force which reaches a high value at a low current, and increases very little with subsequent increase of current. With the size suited to the weight of the car such a magnet would almost eliminate both skidding and surging. I gather that, from the drawings in the paper, the latest form, 26C, contains some of these desirable features. Mr. Gerrard appears to have worked out a solution in which all important points have been successfully considered.

Mr. Mavor.

Mr. S. MAVOR: The improvement effected with the side-by-side arrangement of the brake-shoes might be due in part to the shorter magnetic circuit through the electromagnet and through the rail as yoke, but in this type the magnetic leakage would be greater. The area of surface contact of the brake blocks on the rail would also be an important factor, and it would be interesting to have information as to surface contact of each of the two types.

Councillor Hoey.

Councillor S. HOEY: As a member of the Corporation Tramways Committee, I am only too pleased to have been able to listen to the paper, but I am not at all glad to hear the remark that the last word has been said on the question of electric brakes. I came here to-night thinking that I should hear of improvements in brakes, but I have been disappointed.

Mr. Stevenson.

Mr. G. STEVENSON: The paper is very complete and very full, so far as the technical side of braking is concerned, but after looking carefully over it, I can find no reference to the cost of the various systems described. I think the author should tell us something in this connection, not only with regard to the initial cost of the different types of brake, but also the operating costs per car-mile. I take it that this side of the question was not left out of account in settling the best type of brake to meet the conditions obtaining in Glasgow. With regard to Test Table No. V., I notice that the author gives the approximate speeds in miles per hour, worked out to three decimal places, which is rather unnecessary.

Mr. Gerrard

Mr. GERRARD (*in reply*): Mr. Peck has just made a very interesting contribution to the discussion, which, however, calls for very little reply; his views on the destruction of the equipment and the brake question in general, practically coincide with mine. Regarding maintenance cost, there is no doubt that it must be very high on systems where the old type of brakes are being used for both service and emergency stops. Regarding Mr. Cockshott's remarks, I find that he concurs in all that I have said about the old type of magnet being far from ideal; he also endorses my remarks about the new type of magnet being very powerful, and about the difficulty we all experience with skidding wheels when making quick stops at high speeds. He describes his experiences when making stops at 26 miles per hour on a

gradient of 1 in 11, but these only bear out what I have been saying, namely, that solenoid control, or some similar method of grappling with the high voltage, and thus preventing the motors from being overloaded to the extent of skidding the wheels, is urgently required on all systems using the electric brake. I am pleased to find that he agrees that the solenoid device to some extent reduces skidding. I can, however, safely assert that by solenoid control he could so reduce the work allocated to the motors as to absolutely prevent skidding. He states that the maximum voltage recorded during tests at Leeds was very much lower than at Glasgow, which is quite natural, as the equipments on the two systems are quite different; however, he admits recording 890 volts, which is 50 per cent. too high. The reason why, in my opinion, solenoid control would not prevent the "1908" brake from skidding the wheels, although it would reduce the voltage, is that the design of the brake is against it. As I previously mentioned, this brake is designed to transfer a proportion of the weight of the car from the wheels to the auxiliary track blocks. By doing this we are removing the mechanical load from the wheels while still retaining the electrical load on the motors. We are robbing the motors—which are, of course, for the time being, generators—of their only available source of power, while they are practically running on short circuit, therefore the armatures cease to revolve and the wheels skid. Mr. Cockshott stated that he had seen no surging in Leeds while coasting. This paper only deals with the results obtained in Glasgow, and there was no doubt about surging there. While coasting down a gradient of 1 in 13 on this electric brake, the car would be brought to a standstill; then when the magnets became demagnetised and rose from the rails, the car would plunge forward, only to be brought up again, and so on. In reply to Mr. Maley, I might state that the Glasgow Local Section invited me to write a paper, and I chose this subject for it—firstly, because it was uppermost in my mind at the time, and secondly, because, so far as I know, it is quite a long time since the Institution had a paper on this subject. Regarding my tests being of a rough character as compared with those carried out by Mr. Fell for the London County Council, if I had ever anticipated that the results of my tests would be embodied in a paper and that I should be invited to read it in London, I would undoubtedly have endeavoured to obtain the most up-to-date self-recording instruments; but I think that the instruments which I did use and the methods which I adopted, have given results which are quite conclusive. Had the results from the two cars been within 2 or 3 per cent. as regards the voltage, we would have gone over the tests again, but when we find that the voltage from one car is 1,200 and the other 600, I do not think that a change of instruments would have materially affected the result. Regarding the original Newell Brake, Mr. Maley points out that the motors did the greater part of the work of retardation and the brake very little. That is quite true, hence the reason for designing a more powerful magnet. By referring to Test Table II. (Tests C and D) it will be seen

Mr. Gerrard.

Mr. Gerrard. that we have reduced the current required while coasting on the easy gradient from 12·6 to 3·4 amperes, and on the heavy gradient from 30·6 to 12·15 amperes, which clearly shows that we are transferring the work from the generators to the brake. He also states that solenoid control is not a new idea. That is quite true, but in all probability those who acquired Mr. Newell's patents thought that the brake was quite good enough without solenoid control—in any case, it was dropped. However, I wish to state that neither the present officials of the Westinghouse Company nor I myself knew of such a patent; we started on original lines. I note Mr. Maley admits skidding with his brake when he says, "The most we have ever done with our brake is to cause the wheels to stop momentarily, perhaps once, or perhaps twice, but very seldom twice." This bears out exactly what I found and have shown in Table IV. It is quite evident that if we observe two distinct skids in a stop which is made in 3 to 4 seconds, they can only be momentary; but the fact remains that these motors were overloaded to the extent of skidding the wheels and were therefore doing more than their fair share of the work of retardation. Regarding the slides shown on the screen and the remarks made by Mr. Booth, I do not see that they have any bearing on the subject before us, namely, the braking equipment at Glasgow. He advocates relieving the motors of any share in the retardation of the car and suggests exciting the magnets from the trolley line. This would be quite practical on some bogie cars where there is any amount of room to instal multipolar magnets, but I am afraid that it is impractical in the ordinary 6-ft. wheel-base truck. If we relieve the motors of their share in the retardation, we must substitute something else, and the only way to do this is to increase the size of the magnets, or instal more of them per car. I could not, however, advocate drawing current from the generating station to retard the car when we already have an efficient generating plant on each car; besides, it would be a most dangerous policy to depend on a power station for both propelling and retarding power. For instance, if the circuit breaker were to open at the power station when the car was ascending a steep gradient, the motorman would have to prevent a run-back by means of the hand brake alone. In reply to Mr. H. M. Sayers, I wish to thank him for his very practical and instructive contribution to the discussion and for the remark he made regarding the trouble one has to put up with in order to obtain comparative results from tramcar brakes. He mentions that the steepest gradient we tested the brakes on was only 1 in 13. I am thankful to say we have no steeper gradients at present. He also mentions that it is a disadvantage not being able to apply the magnetic brake before the car leaves the top of a gradient. But if desired, this can quite easily be arranged for. The electromagnets can be applied mechanically in the same manner as any other mechanically applied track brake; so by this arrangement we obtain an efficient track and wheel brake combination, mechanically applied, with the advantage that it can be magnetically applied, either separately or conjointly with

the mechanical gear. When approaching a steep gradient this braking combination can be applied mechanically and the car then propelled over the crest of the incline; when coasting it could be magnetically applied as desired. Mr. Gerrard.

Regarding Mr. Ferguson's very interesting remarks, his views and mine practically coincide. Mr. McWhirter asks for the cross-section of the various magnet cores. The core of the old type of magnet is $3\frac{1}{4}$ in. diameter $= 8{\cdot}2$ sq. in., whereas the core of the new type is approximately 19 sq. in. He is of the opinion that the 25B magnet is too powerful. That is exactly what we found in practice with a 10-ton car. The small new 26C type is the most suitable magnet for our work. We can get a higher retardation from the large magnet, but when coasting it sets up an objectionable surging effect, so we are obliged to part with it and use the small magnet in order to get steady coasting. With reference to the superabundance of iron in the motors, the point before us was to take the motors as we found them, with the high voltage on the brake side, and see what we could do to reduce it. These machines were specially designed for traction work, and I do not suppose that the question of braking the car through the motors was taken into consideration at all when they were being designed. Mr. McWhirter is quite right in assuming that the voltage would be high when operating in conjunction with any ordinary braking combination. It makes no difference to the voltage what type of brake is in use; it is the skid proof device or double solenoid which checks the rise in voltage.

Mr. Maxwell is wrong when he assumes that we use the hand brake at low speeds because the electric brake is inoperative. We can use the electric brake with the very best effect, even when the car is running dead slow, but our motormen are taught to use the electric brake only for emergency and coasting, the hand brake to be used for ordinary service stops. He is anxious to know why our schedule speed is low, when compared with American practice. That question I cannot answer. The Board of Trade determine what the speed shall be on the various sections of the system. As to why we have never introduced air brakes, my answer is that we already have a complete generating system on each car from which we draw our braking power, and our immunity from accidents with electric braking is such that we are not warranted in equipping the cars with air brakes, which would only increase the weight and equipment of the car without giving additional security, as accidents are not unknown on tramway systems equipped with air brakes. It is quite true that an air brake can be tested and applied if necessary before the car is started down a gradient, but an electromagnetic track brake can quite easily be fitted with an attachment for mechanically pressing the track-shoes down upon the rail, and in that way converting it into an efficient mechanical track and wheel brake. When coasting down the gradient the magnets can be energised from the motors and the mechanical attachment released.

Mr. Gerrard. Professor Baily's remarks on surging are dealt with very exhaustively in the paper. When surging takes place, it is usually found that the magnets are too powerful and probably sluggish in excitation, but there is another cause not previously mentioned, namely badly trimmed brakes. If either the track or wheel-shoes, or both, are badly trimmed, the car when coasting will attain a higher speed before the brake acts than when the shoes are properly trimmed, and in that way will set up surging. Regarding the suggestion that skidding could be eliminated by arranging a suitable saturation value for the magnets, I am doubtful of any good resulting from a change in that direction, because skidding does not result so much from the retarding action of the magnets as from the overload on the motors.

Mr. Mavor asks for the cross-section or area of the various magnetic track-shoes. The area of the old type is 23 sq. in., the small new type 23 sq. in., and the large new magnet 26 sq. in. Of course the small new magnet, the 26c, is designed to occupy as little space on the truck as the old type.

In reply to Councillor Hoey, I left it to the members present to judge for themselves; however, I think we have come to a point in electric braking from which we cannot go very much further. The Westinghouse Company and the Glasgow Corporation Tramway Department both deserve great credit for carrying on this pioneer work which has cost them a considerable amount of time and money, as well as careful thought.

Mr. Robertson asks if the "1908" brake does not tend to lift the car off the track. This brake was designed to transfer a portion of the weight of the car from the wheels to the auxiliary track blocks. In my opinion it is a mistake to do so. It should be the policy of tramway engineers to retain as much weight as possible on the wheels, in order to prevent derailment.

The President: I will now ask you to accord a hearty vote of thanks to the author for his paper.

The resolution of thanks was carried with acclamation.

Proceedings of the Five Hundred and Seventh Ordinary General Meeting of the Institution of Electrical Engineers, held in the Rooms of the Institution of Civil Engineers, Great George Street, Westminster, on Thursday evening, April 21, 1910—Dr. GISBERT KAPP, President, in the chair.

The minutes of the Ordinary General Meeting, held on April 7, 1910, were taken as read, and confirmed.

The list of candidates for election into the Institution was taken as read, and it was ordered that it should be suspended in the Library.

The following list of transfers was announced as having been approved by the Council :—

TRANSFERS.

From the class of Associate Members to that of Members :—

Wellington E. Groves. | Edgar J. Kipps.

From the class of Associates to that of Associate Members :—

Thomas Ferguson. | Wm. M. Selvey.

From the class of Students to that of Associate Members :—

Edwin V. Caton.	Albert E. Jepson.
Harold Craske.	Stanley H. May.
Harold C. Heath.	Frank G. Warburton.
Benjamin F. Hill.	Gilbert Whitaker.
Edgar Hoyle.	John W. Wilkinson.

Ratcliffe Wright.

Donations to the *Library* were announced as having been received since the last meeting from L. Crouch, Gauthier-Villars, H. Hirst, A. Marson, H. Sutton, E. and F. N. Spon, Ltd.; to the *Building Fund* from W. A. Del Mar, S. Evershed, W. McGeoch, J. C. Matthews, N. Tesla, H. D. Symons; and to the *Benevolent Fund* from L. Birks, S. Sharp, and W. H. Miller, to whom the thanks of the meeting were duly accorded.

The PRESIDENT read the following list of Council nominations for election to the Council for the ensuing Session :—

MEMBERS NOMINATED BY THE COUNCIL FOR OFFICE, 1910–11.

As President.

New Nomination — S. Z. DE FERRANTI.

As Vice-Presidents.

Remaining in Office
- W. DUDDELL, F.R.S.
- S. EVERSHED.

New Nominations
- W. H. PATCHELL.
- J. H. RIDER.

As Ordinary Members of Council.

Remaining in Office
- W. W. COOK.
- G. K. B. ELPHINSTONE.
- W. JUDD.
- PROFESSOR T. MATHER, F.R.S.
- W. M. MORRISON.
- MAJOR W. A. J. O'MEARA, C.M.G.
- J. F. C. SNELL.
- G. STONEY.
- A. H. WALTON.
- C. H. WORDINGHAM.

New Nominations
- H. DICKINSON.
- J. E. KINGSBURY.
- P. V. MCMAHON.
- R. K. MORCOM.
- S. L. PEARCE.

As Associate Members of Council.

Remaining in Office
- E. RUSSELL CLARKE.
- J. E. TAYLOR.

New Nomination — S. MORSE.

As Honorary Treasurer.

For Re-election — ROBERT HAMMOND.

As Honorary Auditors.

For Re-election
- H. ALABASTER.
- SIDNEY SHARP.

Mr. W. A. CHAMEN: In accordance with Article 45, I wish to nominate Mr. H. Faraday Proctor, of Bristol, as a candidate for a Member of Council. I have the honour to propose him myself, he is seconded by Mr. W. W. Lackie, of Glasgow; and the following are the supporters who have signed the nomination paper: Messrs. H. Collings Bishop, Arthur Ellis, H. D. Munro, E. G. Okell, Herbert T. Sully, C. A. L. Prüsmann, Walter J. Bache, R. A. Chattock, T. O. Callender, David E. Roberts, Theodore Schontheil, and H. J. Hodgson.

I hope every one will understand that I do not take this course in any spirit of antagonism to the Council. It is because I find, with regret, in various parts of the country, and particularly in the West, that this Institution is not looked upon with that favour which I am sure we all wish it were. There is a feeling abroad, I regret to say, outside of London at any rate, that no one has any interest in the election of Members of Council except the Members of Council themselves. I wish to show by this action of mine and of my supporters that that is not the case, and that the members of the Institution can have, if they so wish, a share in the election of Members of Council. Mr. Faraday Proctor, although he may not be known to a large number of London members, is known very well to a great number particularly in the West of England, and I know that he can attend the meetings, and would be a most useful Member of Council. I regret that when last I was a Member of Council I was unable to attend. I think we ought to have members from the Provinces who can attend. I believe this will be the first time that there has ever been a genuine ballot for the election of Members of Council. I feel that the members and associate members all over the country will take a far greater interest in our Institution if they realise that they can all vote. In other Institutions the Council themselves nominate a larger number of members to fill the vacancies than there are vacancies to fill, so that each year there is an election by the members. That has been found a most desirable course, and I would press upon the Council the desirability of following it in future. With these few remarks in explanation, I beg to hand in to the Secretary, as the Article requires, the nomination papers, including the written consent of Mr. Faraday Proctor.

The PRESIDENT: I thank Mr. Chamen for the trouble he has taken in this matter. The Council has the desire fully, justly, and fairly to represent the wishes of all the members, and the action taken by Mr. Chamen is helpful in this direction. On this occasion I wish to remind the members that it is in the province of every member before the election comes on to send to the Secretary suggestions with regard to the names of the Members of Council. It is always an assistance to the Council to know the wishes of the members, and if members send in suggestions they will be duly considered. With regard to Mr. Chamen's nomination, it will be sent out along with the list of names prepared by the Council, and thus put to the vote of all members.

HYDRO-ELECTRIC INSTALLATIONS OF SWEDEN.

By AUBREY V. CLAYTON, Member.

(*Paper received October* 25, 1909, *and read in London on April* 21, 1910.)

It is impossible within the scope of this paper to do more than briefly describe a very small number of the hydro-electric installations of Sweden, but before proceeding with the principal subject it may not be amiss to describe shortly the characteristics of the country, as I find that many people have only a very hazy knowledge of the subject. The general idea is that Sweden is a little place somewhere up North, excellent for tourists and for winter sports, but of the serious side of Swedish life there seems to be no conception whatever. The length of Sweden is 986 miles, or nearly three times the length of England. Its area is 170,713 square miles, or about three times that of England and Wales together. The population is 5,377,713, so it will be seen that it is very sparsely inhabited when compared to England, the average population of Sweden being 32 inhabitants per square mile, while that of England and Wales is about 500 per square mile. The population is more dense in the South, where in one county it goes up to 240 per square mile, while in the North it is only 2·6. It seems remarkable that a country having such a small population should be able to supply itself with all its wants. Industries, such as locomotive building, shipbuilding, carriage and car works, linen, cotton, and woollen manufactures, all classes of engineering and foundry work, electrical trades, electrochemical works, brick and glazed tile works, pianoforte and organ works, etc., are in the very highest stages of development, and whereas the country's requirements of the articles produced in these various trades were formerly important, the products of the home industries now supply nearly all wants, and in many cases even a considerable export trade in them has been built up.

The country is very hilly, abounding in lakes and watercourses, and the falls on these waterways have made it a busy hive for the electrical industry since the commercial development of electrical power transmission. At the same time, it may be stated that the present flourishing condition of many Scandinavian industries is due to the successful commercial development of electricity, whereby cheap power has become generally available. The area of lakes in Sweden is 13,900 square miles, and from this some idea of the enormous quantities of water available will be gleaned. My colleague, Lieutenant Lübeck, has estimated that the amount of water-power available in Sweden is

equivalent to 3,800,000 H.P. Of this only 550,000 H.P. is at present harnessed, so that there is plenty of scope for further development. That the equipment of the falls is proceeding very rapidly, however, may be gathered from the fact that in 1900 only 253,000 H.P. was utilised, or less than half of what is now employed. In the neighbouring country, Norway, there is available 4,800,000 H.P., of which in 1906 only 250,000 H.P. was utilised. However, since the advent in the last few years of new electrical processes for the production of fertilisers from the air, considerable additions have been made to this figure, so that now the falls harnessed, or in course of being harnessed, represent approximately 550,000 H.P., or about the same as Sweden.

The use of water-power dates back to the very earliest ages; and there may still be seen in many places good examples of old-world waterwheels. These wheels were used for a variety of purposes, such as grinding mills or pumps, and very largely for iron works. Primitive blast furnace blowers, and power hammers may be seen at a few places, and some are even at work to this day. These hammers consist simply of a tappet-wheel placed on the waterwheel shaft. Everything is made of wood, except the hammer head itself. They were used largely for working the puddled iron or "Lancashire," as they call it. For these ancient iron industries, which were of small capacities, no transmission of the power was required, as the blast furnaces with the iron works were placed beside the water courses. With the growth of the iron works and the introduction of rolling mills, for which larger powers were required than could be obtained from the individual local falls on which the works were situated, a demand grew up for power transmission in order to bring the power from falls situated a little higher up or lower down the water courses, and concentrate all to the point where the works were situated. This demand for power transmission was in part filled by wire-rope transmission, but this system is very limited as to the distance to which power can be supplied. Some good examples of power transmission by wire rope still exist.

Another system of transmitting power which is of much earlier date than wire-rope transmission consists of a number of wooden beams linked together at the ends and supported at intervals clear of the ground. These linked beams are placed in two parallel lines about 4 or 5 yards apart, and the cantilever supports, which hold them about 4 ft. from the ground, are hinged so as to allow them to be freely pushed or pulled longitudinally. To the ends of each line of these linked beams are attached a pair of connecting rods from cranks on the waterwheel shaft which give a slow reciprocatory motion to the links; one side of the line thrusting, while the other pulls. These transmissions were very widely used for mine pumps and for blast furnace blowers, in which cases the slow reciprocatory motion was very suitable for use at the receiving end of the line, as it was not necessary to reconvert to a rotatory motion. Some of them were quite long, and their efficiency is claimed to be very good.

With the advent of electricity a new era began, and between the years 1885 and 1889 power transmission by this means was touched on slightly. It was not, however, until the invention of the 3-phase alternating-current system that any real advance with electrical transmission was made. The first 3-phase transmission in Sweden was tried in 1890, and in 1893 a transmission on what was for that time quite a large scale was inaugurated. This transmission, the forerunner of the present enormous business in this branch, was of 400-H.P. capacity, and this power was sent from the Hellsjön falls to the Grängesberg iron mines—a distance of about 10 English miles. By courtesy of my friend Mr. Edström, the Managing Director of the General Electric and Manufacturing Company of Sweden, who carried out the original installation at Hellsjön-Grängesberg, I am enabled to give the following particulars of this pioneer power house.

The original plant consisted of four water-turbine-driven generators each of 100 H.P. Three of these are of 3-phase design and supply power to the pumps, haulage gears, hoists, and other machinery at the mines, while the fourth is a single-phase generator for lighting purposes. All operate at 70 cycles, and run at 600 revs. per minute. Current is generated at low voltage and transformed up to about 9,000 volts for the line transmission. It may be remarked that for a pioneer scheme built seventeen years ago the voltage of 9,000 was quite high. The generators are of the rotating armature type, having inwardly projecting field poles, just like an ordinary direct-current multipolar machine. The carcase, or yoke and poles, are of cast iron. These machines very closely resemble the earliest make of American alternating-current machines, and in fact the type was introduced to Sweden by the late Mr. Ernest Danielson, who before his connection with the Swedish Company in 1892 had been a designer of electrical machinery in America. This type of machine, while it presents some advantages, has been abandoned in favour of the rotary field type except in the very smallest sizes.

Before leaving this Hellsjön station, which has no interest beyond an historical one, it may be mentioned that the original machinery installed is still at work 24 hours daily. As illustrative of the enormous development of the use of electrical power, it may be noted that the Grängesberg mines now employ about 6,100 H.P. electrically, and on account of scarcity of power have recently acquired new waterfalls of about 15,000 H.P., and the work of harnessing these electrically is at present in progress.

Alby.—Alby has been chosen among the power stations to be described on account of its having been partly acquired by English capital, and the name may be familiar to many. It is one of the older power stations, and was built in 1898–1899, fifteen months being taken for its completion. The power from the Alby falls (which are situated on the Ljungan river) is used partly for the production of calcium carbide and partly for the manufacture of potassium chlorate. The carbide is exported to all parts of the world, principally to the English

Colonies and South America, while the chlorate of potash is employed in the manufacture of matches.

The original power plant installed at Alby consisted of two generators of 1,100 H.P. each, generating direct current at 220 volts for the manufacture of the chlorate by electrolysis; one 2-phase 26-cycle 2,000-H.P. generator and two 500-H.P. single-phase generators for carbide production; besides two 360-H.P. continuous-current generators for excitation. All these machines are direct driven from horizontal shaft turbines. A few years later the power station was extended by erecting another 1,100-H.P. direct-current generator for chlorate manufacture, and another 2,000-H.P. 2-phase generator for carbide, with corresponding extensions to the chlorate and carbide works. With the addition of some smaller sets for driving light railways, and some auxiliary machinery for making packing barrels, boxes, etc., these extensions brought up the total power installed at Alby to its present figure—9,760 H.P. The current from the 2,000-H.P. 2-phase generators is delivered at 2,000 volts, and is transformed to the voltage required for the carbide furnaces by transformers situated immediately behind the furnaces. 1,000 H.P. is required for each of the larger furnaces, each phase of the 2-phase generator supplying a furnace, while the 500-H.P. generators are of low-voltage type, work in parallel, and supply three smaller furnaces directly. In 1906 the carbide works were still further enlarged, and the power for these extensions is supplied from falls lower down the river at Ringdalen, about 1½ miles from Alby, and is transmitted at 10,000 volts.

We now come to the construction of the power plant. The first portion of the water intake canal is built of ordinary earthwork, and the latter portion near the power house end is constructed of stone masonry, the fall at this point being too high for earthworks. The total length of the canal is 700 yards, of which 170 yards are built of masonry, and there are no less than 280,000 cub. ft. of stonework in it. The velocity of the water in the earthwork part of the canal is 1 ft. per second, while in the stone part it is 1·6 ft. In constructing the earthworks of the canal a sponting or core of tongued and grooved planking has been left in the middle of the earthworks to prevent percolation. From the end of the canal where it opens out into a large basin or settling pond, tubes of wrought iron convey the water directly down to the turbines which are situated in the power house itself. There are seven tubes, five of these are 6 ft. diameter, and two are 8 ft. diameter. Of the five smaller tubes, three supply the turbines of the 1,000 H.P. direct-current generators, and two the turbines of the 500-H.P. alternators and exciters. The remaining two large tubes supply the turbines of the 2,000-H.P. 2-phase generators. The length of these tubes is 72 ft. and the velocity of water in them is 5·5 ft. per second. The turbines work under a head of 69 ft. to 75 ft., of which 15 ft. is obtained from the suction draft tubes, the turbines being placed in flumes on the machinery hall floor, above the tail race level. The length of the tail race is 160 yards, and the velocity of water in it from 2·3 ft. to 3·3 ft. per second.

The base of the power house is built of concrete, the station floor on which the turbines and generators are situated being supported on arches which form separated chambers for the water discharge from the turbines. The power station itself is of brick. As regards the machinery in the power house, such enormous strides have been made of recent years in this direction that it cannot be considered as an example of good modern practice. In this power station the outer cases of flumes of the turbines were made of cast iron, a practice now abandoned for large-sized modern turbines. On one occasion, one of the outer cases burst owing to a flaw in the casting, causing much damage to the station and loss of life, before the water at the inlet gates could be shut off.

Ringdalen.—Fig. 1 shows the drawing of the newer power station at Ringdalen, which also supplies power to the Alby carbide works. At Ringdalen the fall is 52 ft., and in the power station are five 1,100-H.P. single-phase generators, one 600-H.P. 3-phase generator for supplying motor and lighting load, and two 200-H.P. exciters. All the generators supply at 10,000 volts directly, at which voltage the power is transmitted to Alby and transformed down to suit the carbide furnaces and the 3-phase motor and lighting supply. Each 1,100-H.P. generator supplies one carbide furnace and has its own transmission line with step-down transformers, so that they form five complete separate and independent units. All the generators are driven by direct-coupled single-wheel turbines. The length of the water intake canal is 450 yards, and the speed of the water in it is 1 ft. per second. There are six iron tubes to convey the water from the settling pond down to the turbines, one each for the five 1,100-H.P. 3-phase generators and the two exciters. All the tubes are 6½ ft. diameter. The power station is built much on the same lines as that at Alby, but is more modern in its arrangements in the machinery hall.

Gullspång.—The next station to be described is Gullspang, and it possesses several points of interest. This power station is in the southern part of Sweden, and the falls are situated on a short river between the lakes of Skagen and Vänern. The falls are now owned by the Gullspång-Munkfors Power Supply Company, which was formed in 1906 to acquire and develop these Gullspång falls together with some other falls at Munkfors, and to supply the power from them to a number of neighbouring towns, iron works, and other industrial undertakings. The power is transmitted at 40,000 volts, and the greatest distance to which it is at present delivered is about 50 English miles. The level of the water in Skagen is about 79 ft. above the level of the water in Lake Vänern. Lake Skagen has an area of 50 square miles, and forms an ideal natural storage for the water supply, allowing of regulation for the wet and dry seasons. An idea of the value of this natural water storage in Lake Skagen may be gained when it is stated that, whereas the lowest water flow observed in 1906 was 950 cub. ft. per second, it is calculated that by damming up the water in Lake Skagen and regulating the flow, an average flow of 1,600 cub. ft. per

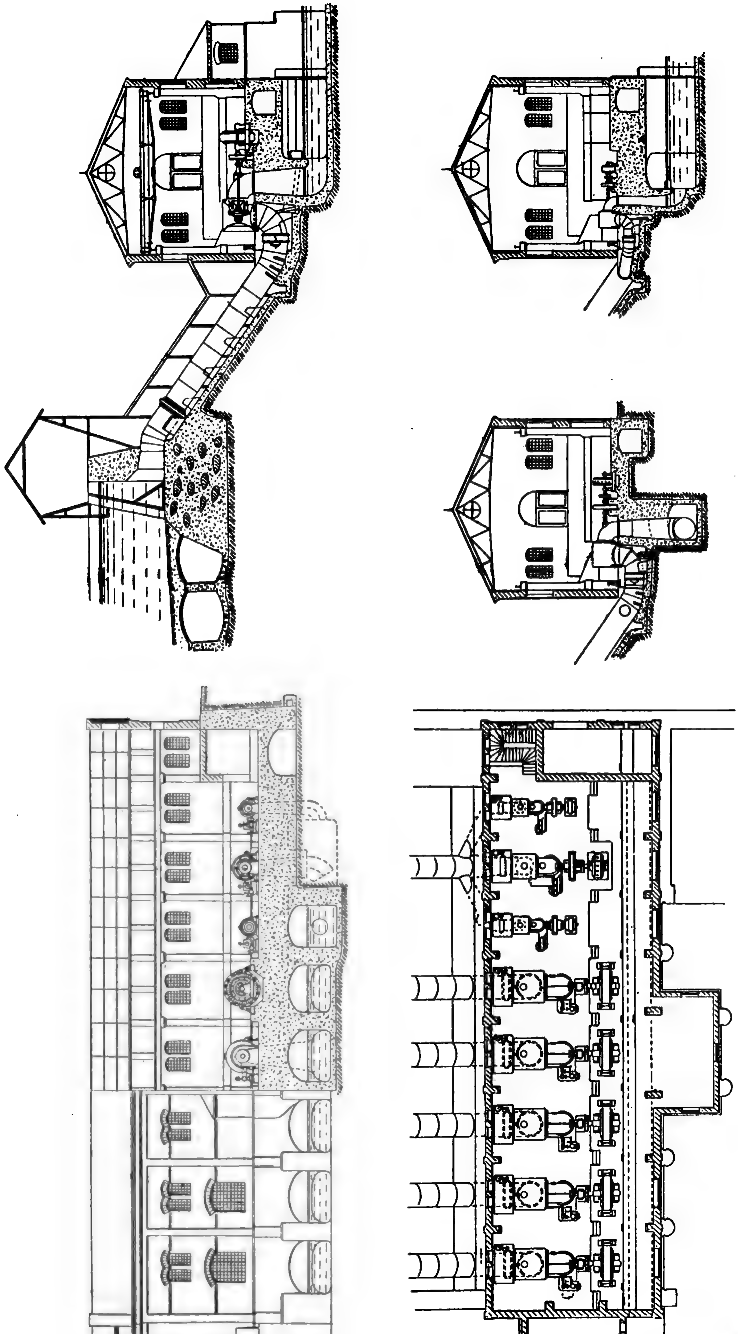


FIG. 1.—Ringdalen Power Station.

second can be obtained all through the low-water period, an increase of 70 per cent. over what could otherwise be obtained. The mean water flow at Gullspång for high- and low-water periods is about 2,550 cub. ft. per second. The distance by land from Lake Skagen to Lake Vänern is at one point only 1¼ miles, but the length of the river connecting the lakes, and upon which the Gullspång power station is situated, is 8 miles. In its course are two falls, or, more strictly speaking, rapids, namely, Gullspång Rapids, having a fall of 67 ft. in a distance of about half a mile, and Årås Falls, of about 10 ft. The Gullspång Rapids are about 5 miles down the river from Lake Skagen, while the Årås Falls are at the outlet to Lake Vänern. The power station is at Gullspång, and it is intended eventually to utilise the second falls at Årås by deepening out the tail race from Gullspång down to Årås. At the point where the power station is situated the river runs through steep walls of rock, and in order to build a dam across the stream, the water had to be diverted from its natural course through a temporary tunnel blasted through the rock. This was, of course, a very costly proceeding, but under the peculiar circumstances no other way of doing the work satisfactorily was possible. This tunnel was about 60 yards long and 30 ft. diameter. After the dam was completed the tunnel was closed up. When the course of the water was diverted through this tunnel and the river bed was laid dry, it was found that the bed of the river did not, as had been expected, consist entirely of rock, but that in order to get to the solid rock considerable excavation would be necessary in the middle and towards one side. As this would have entailed immense expense the original plan of building a gravity dam straight across and supporting it on the solid rock bed was abandoned, and instead an arch-formed dam was built on that portion of the river where the solid rock could not be got to without excavation.

Fig. 2 shows a section of the stream bed and plan of the dam. From it will be seen the bottom of the stream and also the deeper rock formation. The straight part of the dam constructed on the gravity principle, which rests on the solid rock bed, was brought out as far as possible so as to make the arch part short. This latter part of the dam depends for its stability on its arch-like properties, the crown of the arch, as it were, being against the stream or head of water and the arch buttressed or wedged in between the solidly supported ends. By employing this means of construction an enormous saving both in the cost of excavation and of material employed was effected. By a reference to Fig. 2 it will be seen that the section of that part of the bed which would have had to be excavated about equals the profile of the existing dam itself, and if the extra breadth of base which would be required for a gravity dam be taken into account, the cubical contents of this extra portion will be found to be as great as that of the existing dam; that is to say, the amount of material required would have been just double that which has been used, and to this would have to be added the cost of excavation. The front of the dam is faced off with cement,

and the bottom caulked with stamped clay to prevent leakage. A very large number of regulating sluices are provided. In all there are fifty, and they are grouped in ten openings of five sluices each. The sluices are of wood working in I-section steel girder frames. A large opening or spillway in the centre of the weir is provided for clearing off loose ice. A salmon pass and two eel passes are, as is usual, also provided. The water is led from the head race to the turbine house in an open canal.

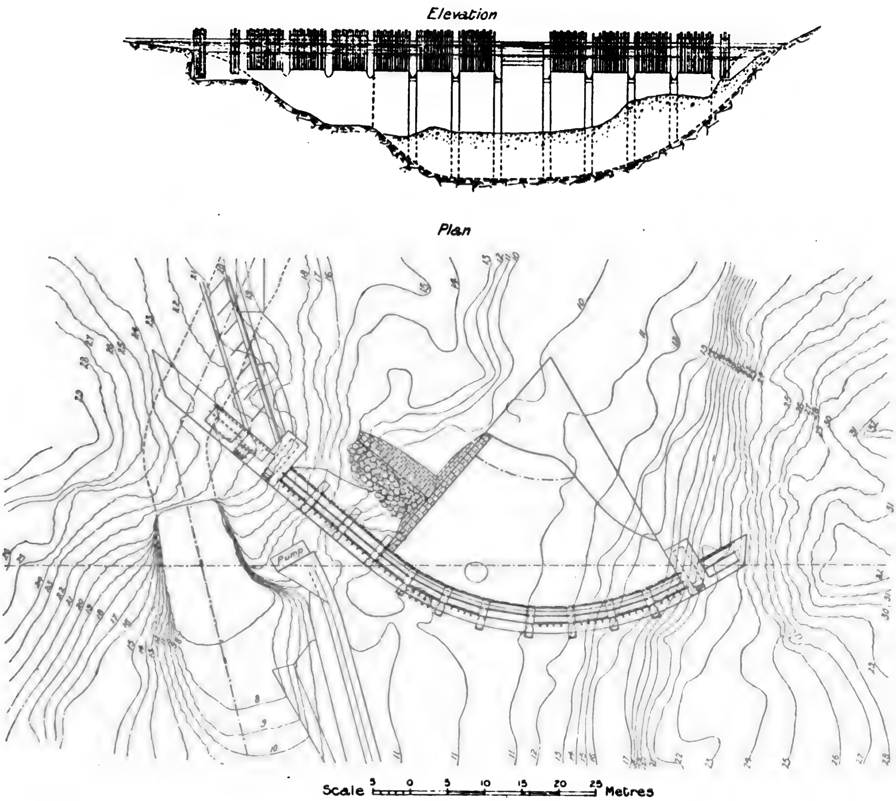


FIG. 2.—Section of River Bed, Elevation and Plan of Dam at Gullspång.

The bottom part of this canal has for a great part of the way been blasted out of rock and is built with concrete walls, while the upper part consists of earthworks. Where the junction between the concrete walls and the earthworks is made, a sponting of concrete prevents leakages, and the earthworks are for part of the way constructed with wood sponting, as was described in the case of the Alby canal.

The power station proper and the forebays are built close together. Fig. 3 shows a section of a forebay with ice-racks, sluices, turbine

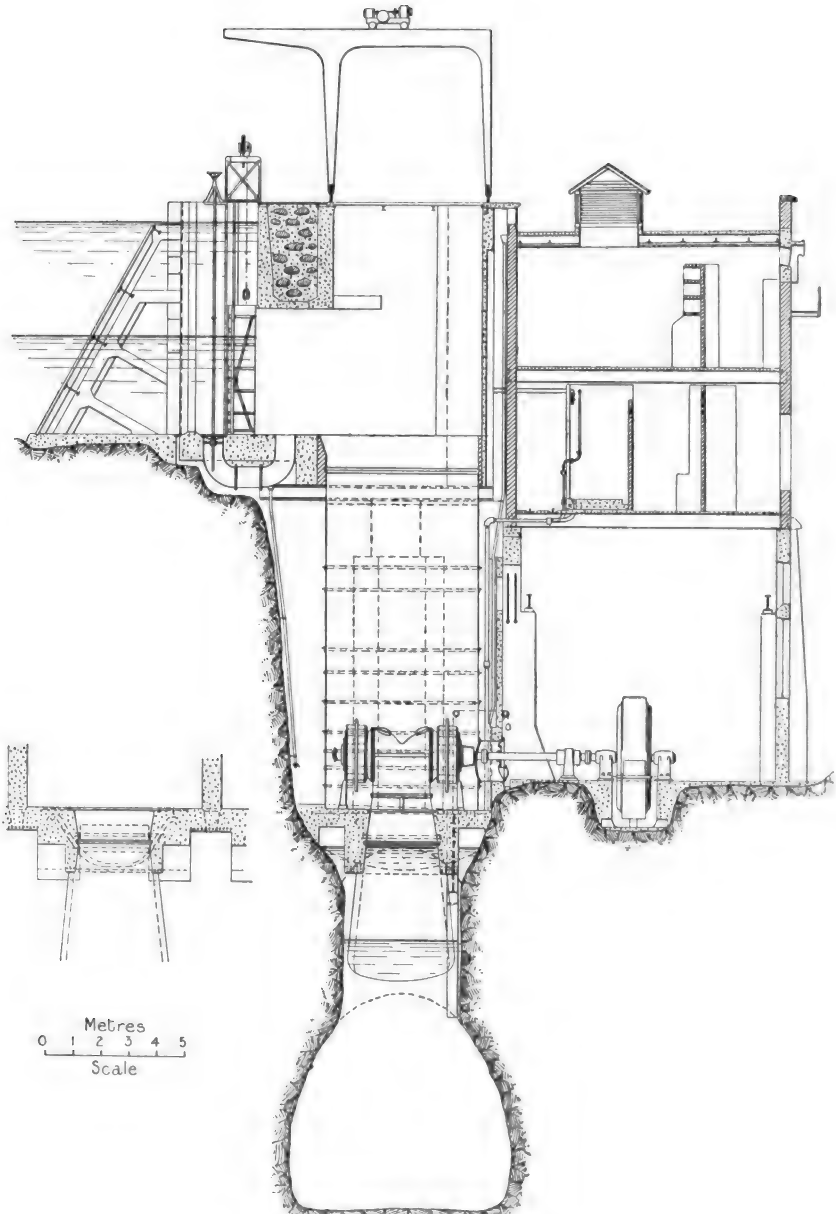


FIG. 3.—Section of Power Station at Gullspång.

flume, turbines with draft tube, tail race, tunnel, and power house. The forebays are built of reinforced concrete, and the power station partly of concrete and partly of brick. The turbines are of twin type, and are placed in open vertical tubes or flumes of boiler plate. These flumes are 43 ft. long and 18 ft. diameter. When completed there will be six turbine flumes, each constructed for a pair of 4,500–5,000-H.P. turbines for driving the main generators, beside the auxiliary turbines for the exciters. Only four pairs of turbines and generators with exciters are installed at present, the remaining two being reserved for extensions. Each of these turbine flumes is separate in itself, and provided with its own forebay, ice-rack, and head-gate. The head-gates are 18 ft. wide and 15 ft. high, and are of an interesting and novel construction, for which patents have been applied for. They consist of cylindrically bent iron plates stayed with horizontal struts, and are provided with oak sliding surfaces. As these gates are too wide to be manœuvred against the water pressure, bypasses are arranged to fill the forebays previous to operating the gates. The gates themselves are raised or lowered by a travelling crane, which can be moved over each sluice. In order to avoid subjecting the materials to the strains consequent on unequal expansion, very great attention was paid to this point in the construction of the forebays, thereby eliminating the risk of cracks occurring in the concrete. Thus each of the forebays stands for itself; they are not connected to each other, and are free from the rock at the sides, being supported solely from the bottom on concrete walls which stand up between the turbine flumes. The joints between the boiler-plate turbine flumes and the concrete floor of the forebays are also of expansion type. In order to effect this each flume tube was well greased before the concrete was stamped in round it, while to ensure a watertight joint between the concrete and the tube, a V-shaped groove was left round the top of the tube in the concrete, and into this groove a packing of tow steeped in paraffin wax was inserted. The pressure of the water forces this wedge-shaped tow packing ring in against the tube, just in the same way as in an ordinary hydraulic ram joint, and makes a perfectly tight joint. The backs of the forebays are made of thin half-circle walls, while the sides are of heavy straight construction. The side walls are held together at the top by heavy straight steel girders, and one pair of the girders forms a track for an 18-ton travelling crane used for erecting or repairing the turbines. It will be noticed on the sectional elevation (Fig. 3) that in the front of the forebays, between the front of this travelling crane rail and the head-gates, there is a heavy filling of ballast. This is intended to counterbalance the force of the water pressure acting against the back of the forebay. As before stated, these forebays are supported solely on walls having their bases at the turbine floor-level, and this ballast is provided to counteract the horizontal tilting force of the water pressure.

The turbines, with their supply tubes and draft tubes, as well as

the concrete walls supporting the forebays, rest on a floor of massive steel girders and reinforced concrete, which is built on the solid rock. This floor is of immensely strong construction, as it has to carry not only the weight of the turbine chambers, etc., but also the volume of water in them. The draft tubes have cement coatings to protect them from rust, and discharge into a tunnel, blasted out of the rock, running lengthwise under the power station. Further down the discharge tunnel opens out into an ordinary open tail race.

The power house building itself is in three storeys, and is built on the solid rock, which has been blasted out to a depth of 33 ft. to accommodate it. The lower storey is constructed of armoured concrete, with a view to better resistance to the damp from the adjacent rock; and, further, the walls of this chamber had to be of great strength in order to support the heavy transformers situated on the iron girder and concrete floor of the second storey. The upper portion of the building is of brick. In the bottom storey, the floor of which is about level with the floor on which the turbines rest, the generators are situated. On the first floor are also the transformers and switchgear, while the top is devoted to the lightning protection devices and outgoing lines. The first floor is level with the ground outside, and on this floor run rails connected with a siding on the main railway lines. A 20-ton electric crane can take goods off the railway trucks and deliver them on to this floor, or drop them through an opening into the machinery hall below, which is served with another 20-ton electric travelling crane. A very complete system of ventilation has been arranged to keep the machinery hall cool, and there are channels running under the floor connected with the generator pits to conduct cool air to the generators.

The runners of the turbines are made with boiler-plate buckets, bent to the correct shape and cast into a cast-iron hub and ring. This method ensures a smooth and even bucket, which minimises skin friction, and so improves the efficiency, and at the same time the bucket is stronger and less likely to be damaged by sticks, stones, ice, or rubbish which may get in, than is a cast-iron bucket. This style of making runners is much employed for turbines working on falls up to about 65 ft., and up to sizes about as large as these—*i.e.*, 2,000 to 2,500 H.P. per wheel. For larger sizes and bigger falls cast-steel runners should be used. The guides or chutes leading the water into the wheel are movable on pivots, and by the movement of these chutes the openings between them are varied, and the amount of water admitted is regulated to suit the power required. This method of regulation ensures the water being always projected at the correct angle to the wheel buckets, and improves the efficiency at light load enormously. Fig. 4 gives the efficiency test curve of the turbines. Regulation of speed is effected by automatic hydraulic regulators operating directly on the shafts connected to the links of the aforementioned movable chutes. The governor balls are driven from the turbine shaft. They control a little valve, and in rising or falling with

variations of speed admit water into either end of a cylinder. The piston in this cylinder operates, through a rack and segment gear, the shaft connected with the movable chutes. Speed regulation with regulators of this class is exceedingly sensitive. Tachograph records taken on the Gullspång turbines show that with the instantaneous application of full load to the turbine running light, or the throwing off of full load, there is a variation of only 5½ per cent. in speed; while for load variations of half of full load the speed varies only 2 per cent., and, what is still more important, there is absolutely no hunting even with these large changes of load.

The machinery in these power stations is much alike, and therefore the electrical plant in one station may be taken as typical of all. The chief interest centres about the hydraulic constructions and general lay-out of the installations. Before leaving Gullspång, however, there is just

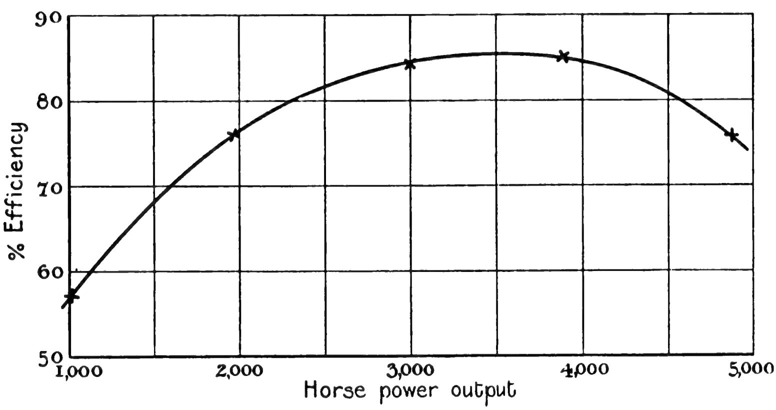


FIG. 4.—Gullspång Efficiency Test Curve of 4,500 H.P. Turbines.

one point, namely, that of the cost of the equipment. At the present time there is installed machinery aggregating 16,500 H.P. exclusive of excitation, and this has been erected at a total cost of £173,000, or about £10 10s. per horse-power. It must, however, be remembered that the hydraulic part of the scheme has been calculated for an equipment when completed of 25,000 H.P., and in order to carry out this extension there is little expense to be incurred beyond the cost of the machinery. Therefore, when completed for its full capacity of 25,000 H.P., the power station will cost £192,000, or about £7 15s. per horse-power.

The Hydraulic Association of Scandinavia, or "Vattenbyggnadsbyrån" (with which the author has the honour of being connected), was retained as the consulting firm for the scheme, and not only prepared the plans, but supervised the carrying out of the entire work.

Graninge.—In the north of Sweden, at Graninge, a new power station has been completed which deserves notice. This station is built for a capacity of 10,000 H.P., of which 5,000 H.P. is now installed and at work. The units are each of 2,500-H.P. capacity, running at 300 revs. per minute, and generate at 5,000 volts, at which voltage part of the power is used in the immediate neighbourhood, while the remainder is transformed up to 40,000 volts for the long-distance transmission.

Figs. 5 and 6 show the plan of the power house and sectional elevation of it. In this case there are not separate feeder tubes for each turbine, but three tubes lead into a common header from which the four turbines are fed. In addition to the gates on the turbines themselves, there are throttle-valve sluices between the turbine flumes and this common header. As regards the electrical outlay of the power station, all the low-voltage or 5,000-volt busbars, apparatus, and outgoing lines have been kept on one side of the building, and all the high-tension 40,000-volt apparatus on the other. The central portion of the buildings is devoted to the turbines and generators, and forms a fine lofty one-storey machine hall. On one side of this hall a three-storey wing is devoted to the switchboard, the 5,000-volt busbars and apparatus, and the 5,000-volt outgoing transmission line, while on the opposite side of the machine hall a five-storey building contains the step-up transformers, etc. The transformers are situated over the feeder pipes and throttle-valve sluices of the turbines, while the three floors above the transformers contain the 40,000-volt busbars, switching apparatus, and outgoing 40,000-volt transmission lines. The turbines are situated in the power house on the same floor as the generators. They operate under a 60 ft. head, and consist of twin wheels mounted on horizontal shafts. Each pair of wheels is mounted in a steel flume, and the discharge is through cast-iron quarter turn discharge pipes and draft tubes, each discharge pipe and draft tube being common to a pair of twin wheels.

As the flywheel effect of the generators is not in itself sufficient to enable the fulfilment of the speed regulation required, heavy flywheels are placed between the turbines and the generators. These flywheels have their own bearings, and are connected through leather band flexible couplings to the turbines, and through fast flange couplings to the generators. Governors of the type previously described are provided, and on test the speed variation was found to be 2½ per cent. for sudden variations of load equal to 20 per cent. of full load. Tests were also made to see if any injurious shocks due to water-hammer took place with an instantaneous removal of full load. For this purpose instantaneous application and removal of full load was made three times in quick succession, but no dangerous shocks occurred.

The 3-phase generators are of 2,150-k.w. capacity each, 50 cycle, 20 pole, 300 revolutions, and, as already mentioned, generate at 5,000 volts. Their tested efficiency is 95·4 per cent. on full load of unity power factor, and 94·2 per cent. on full load of power factor 0·8. The inherent regulation is 1·5 per cent. for unity power factor, and 6·3 for

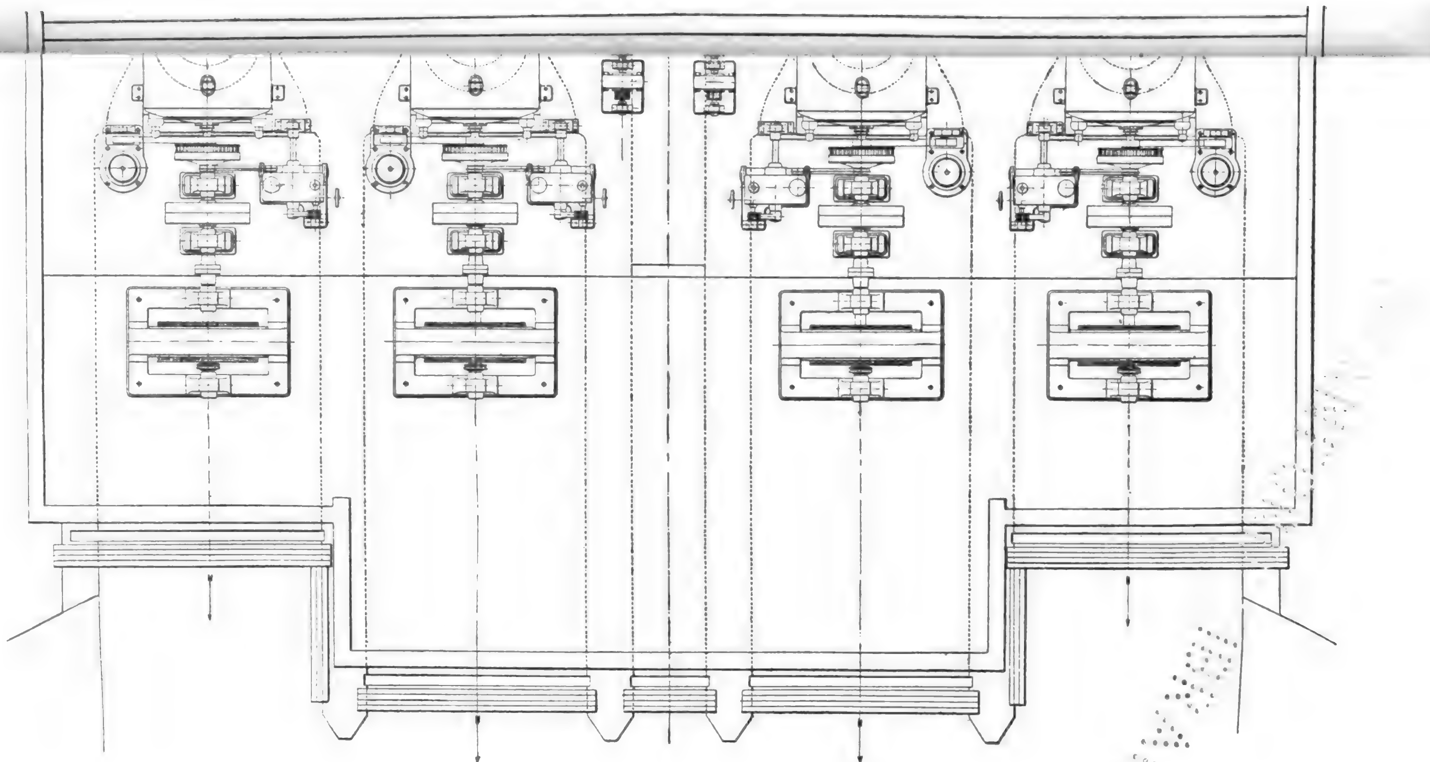


FIG. 5.—Graninge Power Station.

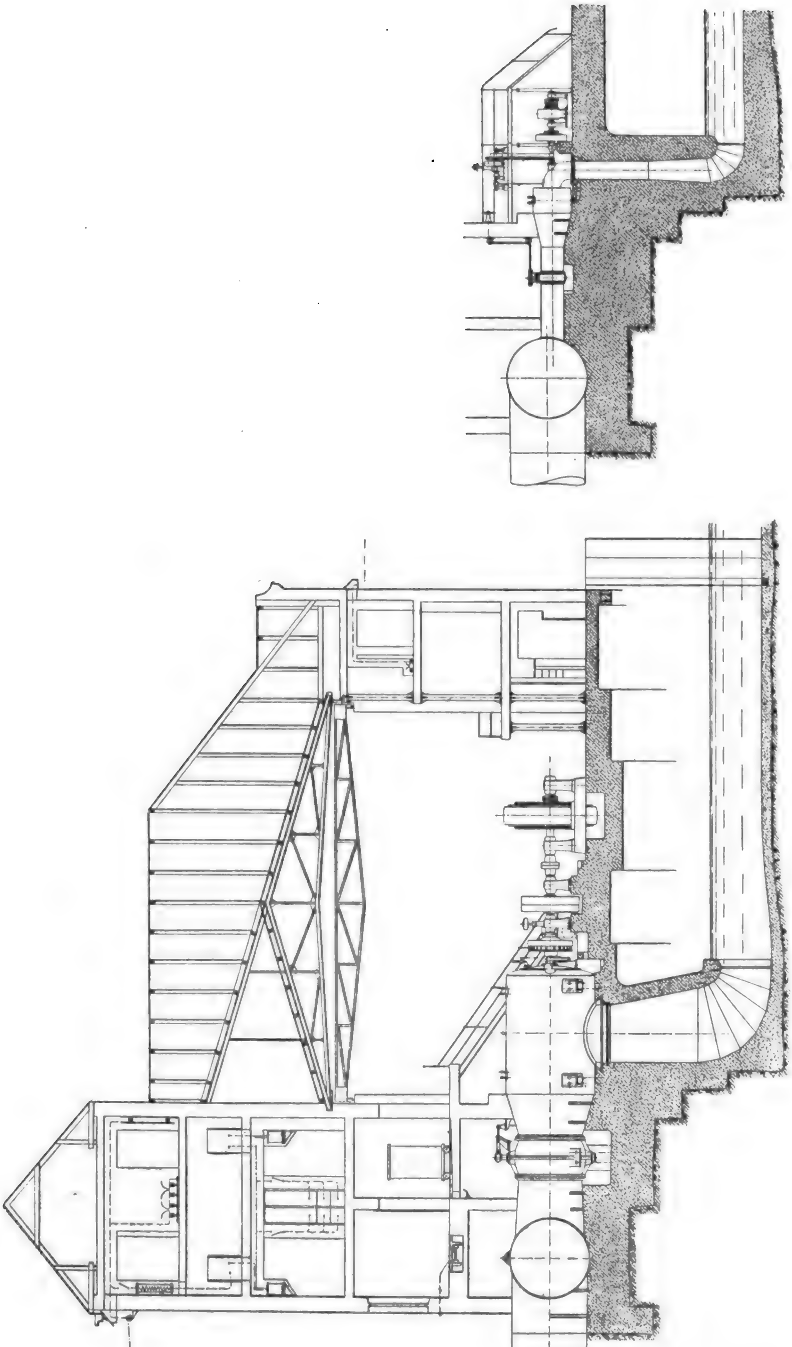


Fig. 6.—Section of Graninge Power Station.

power factor 0·8. It will be remarked that this inherent regulation is very good, but in general the regulation of generators employed in Sweden is not nearly so good, 7 per cent. and 16 per cent. being the more usual figures. It happened, however, that in cases of some large generators tendered for by the firm manufacturing the Graninge generators, doubt was expressed as to the possibility of attaining the regulation figures guaranteed, and so in designing the Graninge generators special attention was paid to the point of regulation, with a view of showing what could be done.

The rotating magnet-wheel with poles, arms, and boss is in one single steel casting, and the pole-shoes are of forged steel screwed to the poles with countersunk bolts. The flanges formed by the pole-shoes hold the field-spools in place. The stator winding consists of bars, one in each slot, and the slots are partially closed. The stator frame with punchings is in halves, and one of the feet on which the frame rests is bolted to the frame. By removing this loose foot the whole stator can be let down on to the field, and so turned round on the shaft to bring any part of the windings situated below the ground-level into a convenient situation for inspection or repairs. The bearings are of the ordinary spherical-seated self-aligning type, with babbit linings and ring lubrication.

Almost all the Scandinavian hydraulic power stations are employed for power transmission, hence they nearly all employ 3-phase generators, and with the exception of the varied constructional details of different designers and manufacturers, and the modifications due to local circumstances, such as high- or low-voltage generation, etc., the generators described may be taken as typical of the general run of plant in Scandinavian hydraulic power stations. With the exception of a few electrochemical works where low periodicity is necessary, 50 cycles has generally been accepted as the standard periodicity. The new State power scheme which is building at Trollhättan is, however, designed for 25 cycles, partly with a view to the use of the power for railways. The City of Stockholm primary transmission is also at 25 cycles, but with these exceptions it may be said that for supply companies 50-cycle 3-phase is universal. This is a very great convenience, as it simplifies matters and standardises plant considerably.

Fig. 7 shows drawings of a very interesting generator at Svälgfos, of 10,500-k.w. capacity, 10,000 volts, 50 cycles, and 250 revs. per minute. This machine was built by the General Electric and Manufacturing Company of Sweden, to the designs of Mr. Holmgren, the chief designer of 3-phase generators to that company. It is one of four supplied to the Notoddens Saltpetre Works in Norway. In this generator the steel poles and ring are cast together, and are supported on a cast-iron arm system. The magnet ring and poles are divided transversely, and an air duct is left between the halves. The width of iron axially in this machine is no less than 49 in., the bearings are of ring lubrication type, and are provided with water cooling in case it be required—this has, however, never been necessary. Using water

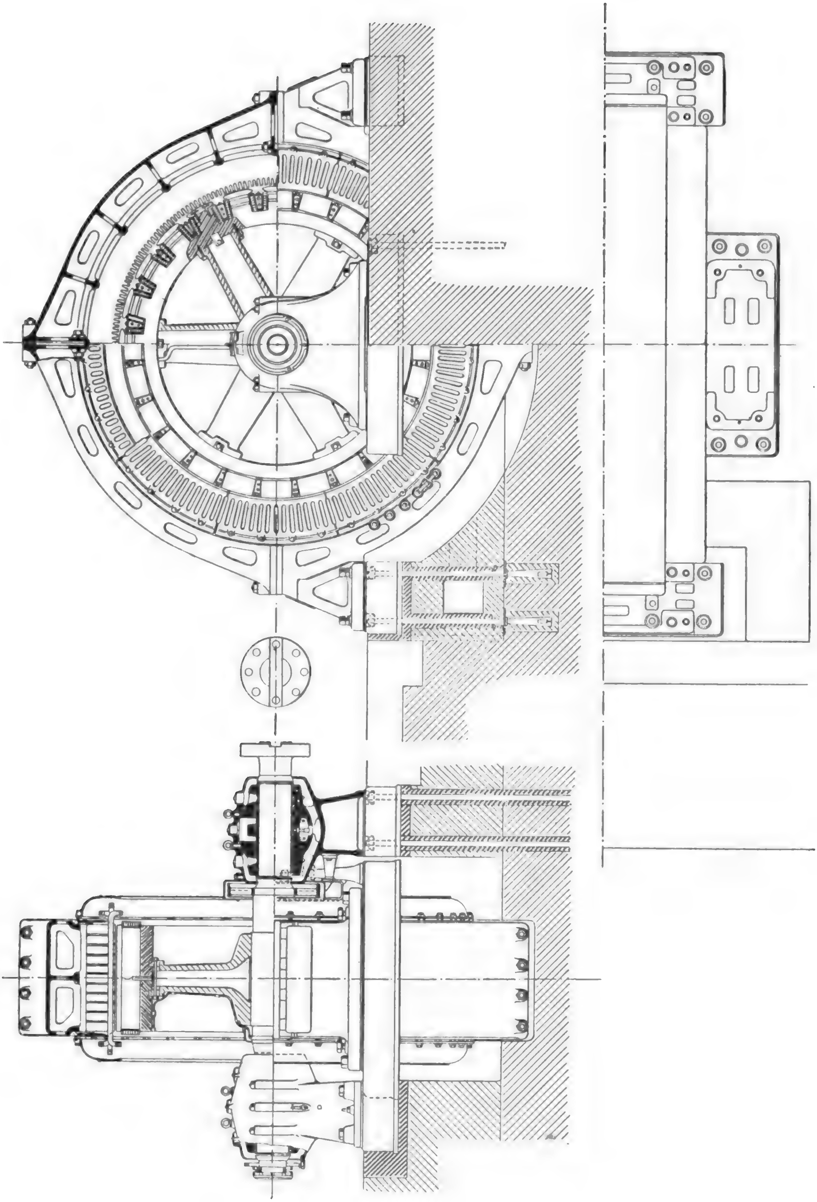


FIG. 7.—Svälgfos 10,500-k.w. Generator.

cooling, however, reduces the temperature of the bearings 10° C. ordinarily. It will be noticed that the stator is in four pieces. This was necessary because the generator had to be slung on wire hawsers across a gorge to get it to the power station, and hence the parts were required to be as light as possible. Although these generators are of enormous output, 10,500-k.v.a., they have been quite eclipsed in point of size by other generators which the same company are building for the above-mentioned Trollhättan State power scheme. These are of 12,500-k.v.a. output, and recently the company has received orders for generators for Rjukanfos, which are of 14,500-k.v.a. capacity. There are two unique generators, built and designed by the same company, working at Brattfors. They are of 2,000-H.P. output each, and generate at 20,000-volts direct, at which voltage transmission is made, no intervening transformers being required. There are many instances of 10,000-volt directly generating and transmitting plants in use, even with machines down as small as 250-k.w. output, but these 20,000-volt generators are the only ones of their kind in Sweden. Another rather interesting generator, designed and built by the author, is one in which no machining has been done to the stator frame. The diameter of the stator of this machine was larger than could be turned in any of the machine tools available, and so the segments of the stator punchings were built up against a ring of 1¼-in. bolts passing through the rough cast-iron frame. These bolts at the same time serve the purpose of clamping the press-rings against the packet of laminations after the latter was built up. It often happens on old machines that the laminations shrink, probably on account of shrinkage of the insulation material between the plates. In order to safeguard against the possibility of the entire package of laminations dropping out of the stator frame, should the upper half of the latter be lifted after some years when the laminations had shrunk, ½ in. steel pins were passed through holes in the laminations and the cast-iron flanges on each side of them and riveted over after the laminations were built up in place. This machine has been running night and day at full load and frequently for long periods (weeks at a time), at considerable overloads since the beginning of 1906, but no loosening of the laminations can be noticed, although it has been subject to frequent short circuits.

Having digressed to describe briefly the subject of generators we will now return to Graninge. The current from the generators is led to the 5,000-volt busbar-room for distribution to the outgoing lines of the 5,000-volt transmission and the primaries of the step-up transformers. This room is on the ground floor-level, and in it are situated all the necessary transformers for the measuring instruments, the oil switches, and connectors. All busbars are laid in closed tunnels, and the only openings in these tunnels are at junctions to the busbars. Further it has also been arranged that the only insulators supporting the busbars are placed at these openings, so that they are easy of access for inspection, etc. The distance from the conductors to the walls of these tunnels is 6 in. for the 5,000-volt leads,

and 12 in. for the 40,000-volt. All the busbar connectors, instrument transformers, etc., are isolated and placed in respective fireproof cells. The switching apparatus is very simple, no fuses are used, oil switches with maximum relays taking their place. Between the generators and 5,000-volt busbars there are maximum relay oil switches, and likewise the 5,000-volt outgoing line is provided with maximum relay oil switch. Each generator is provided with its ammeter, voltmeter, wattmeter, and synchronising apparatus. The 5,000-volt busbars are in sections, so that the generators can be worked on separate sections or in parallel as required. Between the 5,000-volt busbars and primaries of the step-up transformers there are no oil switches, but simply link connectors. The transformers are of single-phase type, of 720-k.w. capacity each, and are used in sets of three to form complete 2,160-k.w., 3-phase transforming systems for each of the three generators. On the high-tension secondary side of the transformers are 3-pole maximum relay oil switches for each set of transformers, and beside these there are connector links which permit of coupling any one of the transformers on to either of two sets of high-tension 40,000-volt busbars. There are two outgoing transmission lines, each having its maximum relay oil switch, and they can be fed from either of these duplicate sets of 40,000-volt busbars by means of connectors.

As is well known, great precautions must be taken against the effects of lightning discharges, or over-tension due to other causes on aerial transmission lines of this kind, and the difficulties increase enormously when the transmission voltages get into high figures. Moreover, the very severe climatic conditions obtaining in Sweden, especially so far north as this power station is situated, call for special attention to this point. In the present case zinc roller tension limiters and horn lightning arresters are used, while powerful impedance coils are placed between these protective devices and the 40,000-volt busbars. On each phase of the outgoing lines there are two horn arresters in series, one of which is connected in parallel with a water resistance. The water resistances consist of very large glazed earthenware bent pipes filled with water. The up-bent open ends of the pipes are covered with loose brass covers through which are brought conductors terminating in spiral wire ends immersed in the water. The horns and resistances of each phase are placed in separate chambers. It has been found that a gap of 32 mm. for the first horn and one of 40 mm. for the second horn, which is in parallel with the resistance, give the best results. Another means of preventing over-tension on transmission lines, and one which has proved exceedingly effective, is to make connections from the lines to earth through fixed resistances. The resistances are adjusted so as to allow a very small current constantly to flow to earth, and these connections to earth lead off the small static charges which would otherwise accumulate on the line. Experiments have been made with carbon and other classes of resistances for this purpose, but a circulating water resistance has proved best.

We now turn from the apparatus to the switchboard itself, which is placed on the first storey over the 5,000-volt busbar-room. It is in the form of a circular sloping-top desk, while behind this desk are a number of cast-iron pillars on which are mounted the instruments corresponding to the switches on the panels of the desk switchboard. All the switches situated in different parts of the building are electrically controlled from the switchboard, as well as all rheostats and also the turbine gates, so that from this point the entire station is controlled. Signal lamps show whether the switches are closed or open. The board being of circular form permits an operator standing opposite to it to see all the instruments at once without running from one to the other, and, moreover, he has a full view of the entire station and the transformer cells, as there is a clear space to the machine house at the back of the instrument pillars. The transformers, as mentioned, are of single-phase type used in sets of three, oil insulated and water cooled, having the water circulating through cooling coils immersed in the oil. Each is placed in its own little fireproof cell, the cells being in a row on the first storey of the 40,000-volt building, on a level with, and immediately opposite the switchboard alcove. The cells have fireproof iron doors front and back, the doors on one side opening to the machine hall and on the other to a long gallery having rails leading to a repair shop. The transformers stand on little trucks, so that any transformer can with the greatest ease be removed and replaced. The doors of the transformer cells on the machine hall side usually stand open, mainly with the object of seeing if the circulating water for the cooling coils is running properly. This can be observed from the machine hall and the switchboard alcove. There are signals to show if the temperature of any transformer rises too high, and in case of fire the iron doors of the cells can be instantly closed by operating a lever.

The cooling coils of the transformers may present some novelty, in that instead of having one or a few circulating pipes of large diameter, or a water jacket, they consist of a number of small diameter copper tubes placed in parallel, like a little water-tube boiler. Fig. 8 shows drawings of the box and cooling coils. In this construction the tubes are expanded or sweated into headers which form one side of distribution boxes for the inlet and discharge of the circulating water. The entire system of cooling tubes is placed at the top of the transformer box over the transformer itself, and is attached to the transformer box lid, so that when the lid is removed the coils are removed with it. By employing this construction an enormous cooling area can be got into a very small space, practically the only limit to the room required for the cooling coils being the amount of space which must of necessity be left between the tubes in order to obtain good circulation of the oil. Moreover, the cooling coils are at the top of the box, where the oil is hottest, and hence in the most effective and best position. A very complete arrangement is provided for tapping out the oil, boiling, and refilling. It consists of a system of pipes to and from the transformers connected with oil-boiling tanks.

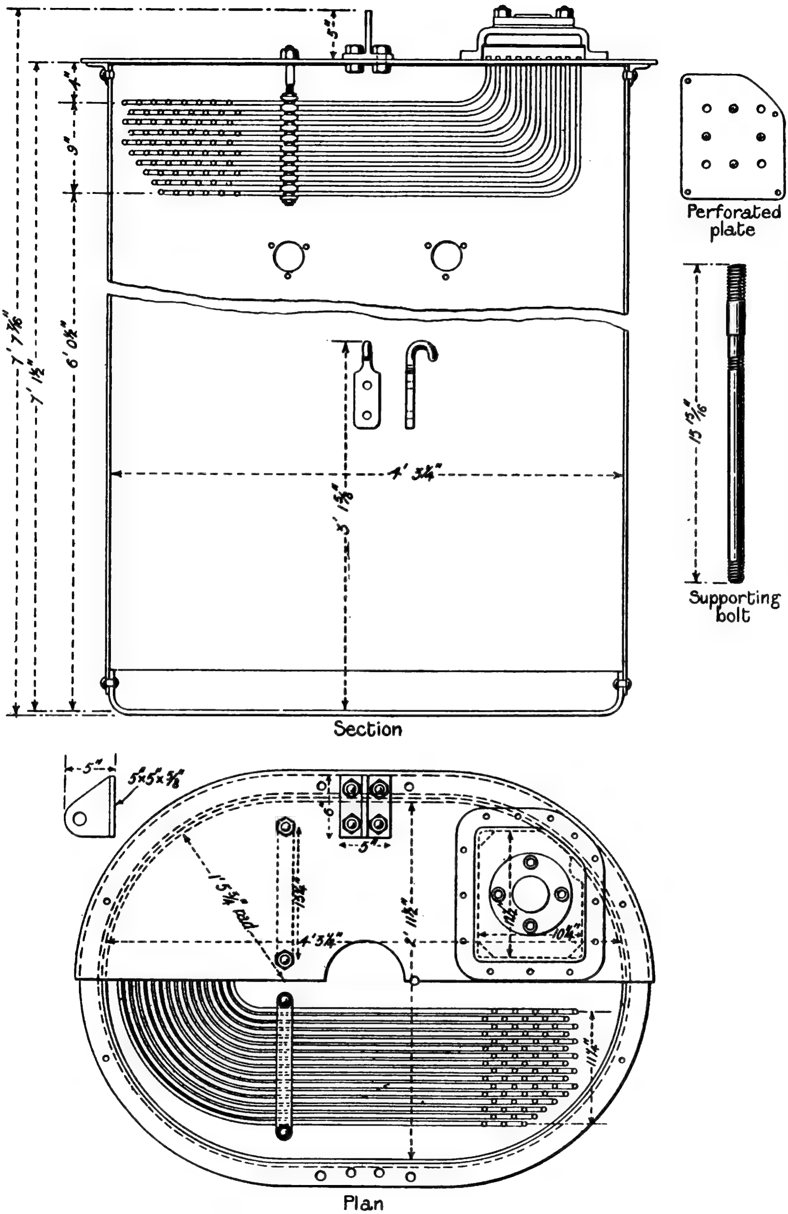


FIG. 8.—Box for Graninge 720-k.w. Transformers.

While on the subject of transformers it may be in keeping to offer a few general remarks on them. By kind permission of Mr. Edström, I am here enabled to show drawings (Fig. 9) of the first 3-phase transformer made in Sweden in the year 1890 by Jonas Wenström, the well-known inventor, upon whose inventions the present General Electrical and Manufacturing Company of Sweden was founded. It will be noticed that the primary and secondary windings are in two spools per leg or phase placed one above the other. The end yokes are in the form of hexagonal plates, and their lamination is crosswise to the lamination of the leg-pieces. With modifications of the arrangements of the windings and the introduction of air-blast cooling, these transformers were made up to quite large sizes—to wit, 700-k.w. output. The use of oil-cooled transformers has, one might say, only of recent years become general in Sweden; in fact, the writer believes that the first oil-cooled transformers built in Sweden for general commercial use were made at the Clayton-Unger Works in 1903. On account of the larger

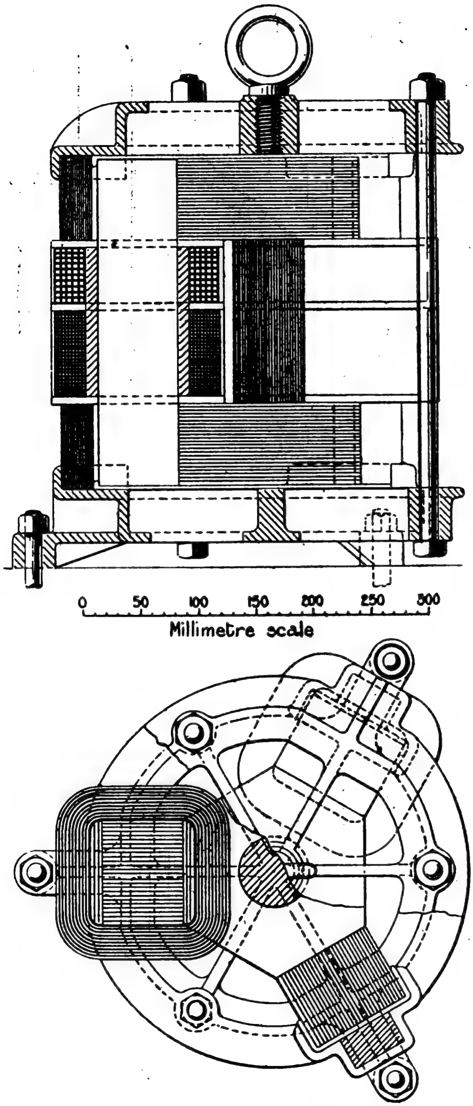


FIG. 9.—Original Drawing of First Swedish 3-phase Transformer.

units now employed and the high voltages used for transmission, the use of oil-cooled transformers has become general. In the water-driven power stations it is, of course, easy to get water for cooling purposes, but in most sub-stations it would be a very troublesome job to have to arrange for circulating water, and hence in them oil-insulated transformers with ordinary air cooling must be used. When oil transformers were first built they were of small capacities, and an ordinary cast-iron or wrought-iron box large enough to hold the transformer gave quite sufficient cooling area to dissipate the heat due to the losses of the transformer. As the sizes became bigger, however, extra radiation surface had to be obtained, and this was done by casting ribs on to the outside of the boxes. As demands arose for still larger sizes, it was found that the oil would not transmit its heat quickly enough to the smooth inside circular box in order to get the full advantage of the increased area of the outside ribs. The suggestion of casting radiation ribs on the inside as well as on the outside of the boxes was a failure, the difficulties in casting being too great; and, in fact, even with ribs on the outside alone, the percentage of wasters in casting was very high. Therefore the next step was to make the walls or sides of the boxes with a very deeply corrugated section, in which case the area exposed to the oil inside and the air outside was practically the same. Even these boxes, when of great depth, were difficult to form and cast, and therefore they were cast in sections 20 in. deep and bolted together with a lead packing between. These sections were of fixed diameter and represented roughly the losses of a given size of transformer, so that with increased size a greater number of sections were added. Thus, for instance, a 2-section box with top and bottom would be for a 100-k.w. transformer, a 3-section box for a 150-k.w. transformer, and so on. These boxes, however, became very heavy and costly in larger sizes, and were abandoned in favour of boxes of wrought iron having similar deep corrugations. As in the case of the previously described water-cooled transformer boxes, the idea of keeping the radiation surface concentrated towards the top of the box where the oil is hottest has been carried out in these air-cooled boxes also. The small cistern seen in the illustration on the top of the box is provided to allow the extra space required by the oil when hot, on account of its expansion, and to keep a constant head of oil pressure against the lid of the box. This is necessary to prevent moisture condensing on the under side of the lid in cold weather, which happens if an air space be left between the top of the oil and the lid of the box. Such drops of moisture will fall through the oil on to the transformer, and may cause serious damage. The oil in this little cistern is connected to the main body of oil in the transformer box by a small tube, the upper end of which is some inches above the bottom of the little cistern, so that any moisture that may condense on the under side of the lid of the little cistern will not be drawn into the transformer box, but will lie at the bottom of the little cistern, and can periodically be drawn off from this through a pet-cock. The bottom of these boxes is circular

and is of ¼-in. boiler plate, and the top part is corrugated and of 14-gauge sheets. Another idea of the heavy circular bottom is that it will stand pinching with crowbars and other rough handling in transport in places where proper lifting devices are lacking. In order to stop small leaks the whole box is galvanised after it is riveted and complete. The eventual successful commercial evolution of these boxes is in a large measure due to Mr. Alfred Fraser, of Messrs. John Fraser & Sons, Millwall, the makers of the boxes, and the author would here like to express his thanks to Mr. Fraser for his invaluable aid in this respect, for while it may superficially appear a simple matter to make such boxes, the technical difficulties met with were very great indeed. It is remarkable what a difference there is in the radiation properties of cast-iron and wrought-iron surfaces.

We come now to the transmission line at Graninge. The greatest distance of transmission from Graninge is about 40 English miles. There are, of course, much longer transmissions than this in service in Sweden: for instance, Hemsjo, 96 km.; Yngredsfors-Varberg, 90 km.; and many very long transmissions are in course of construction. It has even been suggested by the State engineer of the Trollhättan Falls to transmit power from there to Copenhagen, a distance of about 350 km., including 8 km. across the sea between Sweden and Denmark. The Graninge line consists of three single wires of 4·5 mm., about 0·18 in. diameter, carried on wooden poles. The pin of the top insulation is mounted on the wooden pole directly, while the two lower insulators are supported on an iron cross-bar. The insulators are of triple petticoat type, made in two pieces cemented together and supported on iron pins fixed to them by a tight packing of oakum between the pin and the inside of the insulator. Formerly it was customary to cement the insulator caps to the pins, the cement used being mostly the litharge and glycerine mixture, but with this cementing it was found that the insulators split, owing to unequal expansion, with the extremes of heat and cold pertaining to the Swedish climate.

The wires are suspended in positions corresponding to the tips of an equilateral triangle, the distances between wires being 50 in. The distance of span between the poles is about 45 yards generally, but at river crossings there are two spans of about 140 yards each, and one at the estuary of nearly 400 yards. In the case of this latter span the conductors and their insulators are supported on triangular frames which are suspended from a steel hawser. The steel hawser passes over rollers on towers 120 ft. high, situated on the opposite shores, and is anchored to rocks at each end. Where transmission lines cross public highways or railways the law requires that such crossings shall be protected so that in the event of a conductor breaking the free end cannot fall down and thus be dangerous. This is effected by enclosing the transmission lines at these points inside a casing of iron lattice work supported on iron lattice poles situated each side of the crossing.

All the preceding power stations described are built with horizontal shaft turbines, and are typical of the most general run of power

FIG. 10.—Interior of Power Station at Näs, Horndal, typical of the Vertical Shaft Turbine and Umbrella Type Generator System.

stations. In many cases, however, vertical shaft turbines and generators of the umbrella type are employed, principally on very low falls, where this type offers advantages. In these cases the turbines are placed in ordinary open flumes, over the top of which is the floor of the generating-room, and the advantages are chiefly as regards variable levels of backwater in the tail race as well as cost. Fig. 10 shows the interior of a typical power station of this class.

In the attempts made to get up high speeds on low falls quite freakish designs are sometimes met with. It may be remarked here that the Swedish practice in this respect is quite different to the American custom of employing gearing to increase the speed of generators driven from slow-speed turbines, in Sweden direct coupling being the rule. Only one case of gearing being used has come under the author's notice there, and the users of it would be glad if they could now dispense with it. At Nyqvarn there is a power station in which the turbine units consist of two pairs of wheels—that is, four runners—with vertical shafts. The fall in this case is on 13½ ft. and the speed of the turbines is 150 revs. per minute. The quadruple turbines are of 500 H.P. Each pair of turbines has a common discharge, the upper pair of wheels having a short cement draft tube. Fig. 11 shows an arrangement of twin turbines of 680 H.P., 107 revs. per minute, working at Avesta Lillfors, on a 10-ft. fall. This equipment was designed specially to be placed in an existing flume intended for an older type of single turbine. It will be noticed that the upper wheel has a draft tube, while the lower wheel does not require one. This is a good instance of a case where vertical shaft turbines should be used. It will be noticed in the figure that the level of the backwater is sometimes considerably higher than the upper part of the discharge case of the upper turbine, while, on the other hand, during periods of low backwater, the water is only level with the bottom of the lower wheel, and the draft tube of the upper turbine then comes into use. If in a case of this kind horizontal shaft turbines had been used, the backwater would at times have a considerably higher level than the floor-level of the generator station. This would have necessitated placing the generators in a sunken chamber, the lower part of which would have to be watertight as the backwater would at times be higher than the floor-level of the power house.

Another class of turbine generator set which is very interesting, and for which Mr. Böving has obtained patents, consists of two wheels running in opposite directions, the shaft of one being hollow and having inside it the shaft of the oppositely rotating turbine. To these two shafts are attached respectively the field and the inductor of the generator, both of which rotate, but in opposite directions. The result is that, for a given periodicity and speed, the generator has only half the number of poles that would be required if the field alone rotated; in other words, it is equivalent to doubling the speed of the generator. Several of these have been at work at Hellefors for many years past, and are quite satisfactory. In vertical shaft turbines the rotating parts

have, of course, to be suspended, and with the generator rotating field, the long and heavy vertical shaft, and the turbine wheels themselves, it will be seen that the weight to be supported is often very great. Many unsuccessful attempts were made to take up this weight on ball bearings, but now it is almost general to use hydraulic bearings, which float the

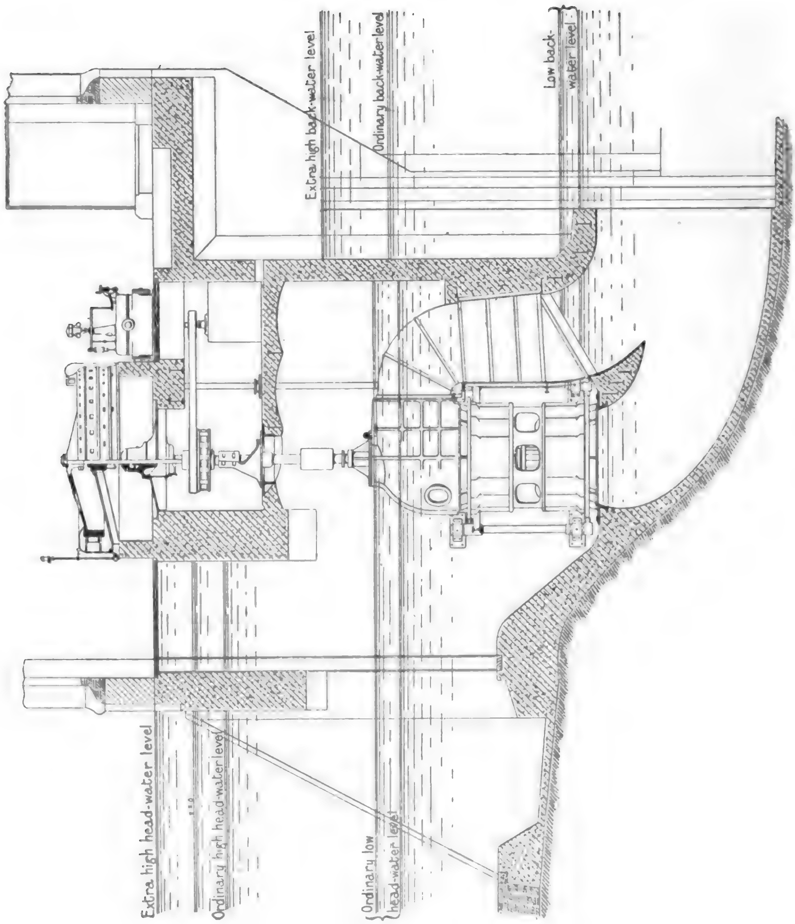


FIG. 11.—Avesta Lillfors Power Station.

entire system where the weight to be supported is too great to be taken upon the ordinary *lignum vitæ* turbine footstep. Fig. 12 shows another unique case, a power station at Korsnäs, in which no less than four pairs of turbines—that is, eight wheels—are used on one shaft. The fall in this case is only 6 ft., and despite the use of eight wheels, the speed is only 107 while the power is only 420 H.P. Installations with

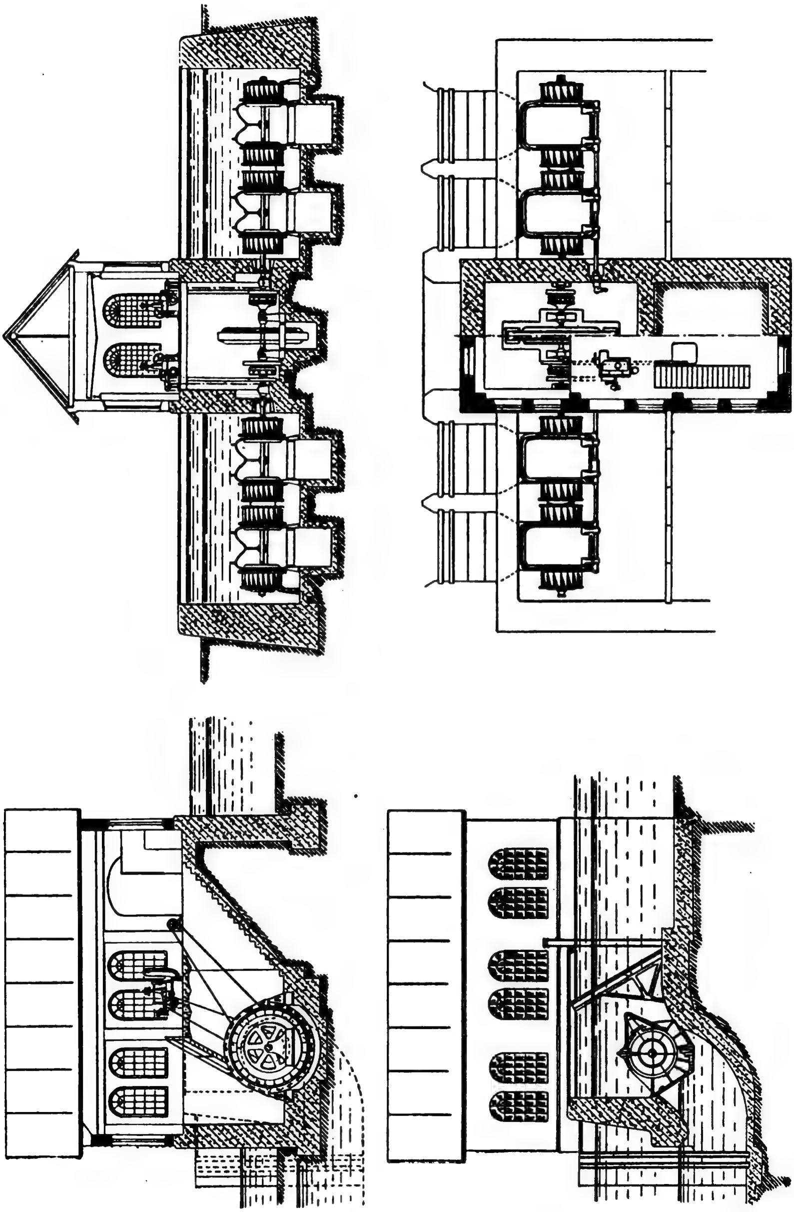


FIG. 12.—Korsnäs Power Station.

such very low falls utilising enormous quantities of water per horse-power developed are, of course, excessively costly compared with their power output. This can be best seen when it is remembered that the same turbine wheels used in this case would, on a fall of, say, 40 ft. (that is considerably less than the fall in any of the previously described power stations), develop not 420 H.P., but about 7,000 H.P., and the same applies more or less to the generators. Twin wheels are, of course, the ideal; but in many cases quadruple wheels must be used to enable the use of large-size electrical generators at reasonably high speeds. Of course, on high falls the obverse obtains, and in such cases single wheels having high peripheral velocity are used in order to get reasonable speeds for the generators. A single-wheel turbine of this class, with an output of 3,300 H.P., is in operation on a 290-ft. fall at the works of the British Aluminium Company, at Stangfjorden, Norway. Even with this single wheel of large horse-power capacity the speed is 300 revs. per minute, and at this speed the generators, which are of continuous-current type, had to be divided into two units of 1,100 k.w. each.

On high falls, and even on only moderately high falls where pipe-lines are used, very great precautions must be taken against the dangers of water-hammer arising from the operation of the turbine gates with sudden variations of load. To protect against these, relief bypass valves are used, which open automatically in the case of the water supply to the turbines being suddenly cut off, and thus prevent any sudden checking of the velocity at which the water is flowing in the pipe-line. On still higher falls Pelton or impulse-type wheels must be used, but I do not know of anywhere in Sweden where wheels of this type are at work. There are, however, two installations being carried out in Norway where Pelton wheels are being used. One of these is at Tya, where a head of about 3,300 ft., probably the highest in the world, is utilised to develop about 70,000 H.P.; the other Pelton wheel power station is at Rjukanfos, also in Norway, where the head is about 1,000 ft. The units at the latter station will be of 14,500 H.P. each. It is interesting to note the low capitalisation cost of these latter big schemes. From calculations made by my Association, the Hydraulic Association of Scandinavia, the installation at Tya is estimated to cost about £525,000, or £7 10s. per electrical horse-power developed.

Where open intake water canals cannot be built—such, for instance, as on sloping ground—wooden pipe-lines are often used for the sake of cheapness. They are made of wooden planking about 3 in. or 4 in. thick, and bound at frequent intervals with strong iron hoops, the spacing between the hoops being dependent upon the pressure due to head of water in the pipes. These wooden pipe-lines cannot, of course, be used with advantage on anything but moderate heads, and they are often used for the first portion of a long, sloping pipe-line until the head gets too great.

DISCUSSION.

Mr. J. F. C. SNELL: Such an adaptation of the great forces of Nature as these hydro-electric plants, while not applicable in England to any great extent, must at least appeal specially to those of us who have to do work abroad. I notice that the author gives the price per electrical horse-power of some of the completed power stations as £7 10s.—that is to say, £10 per kilowatt installed. I should like him to amplify that figure, and give us the price per horse-power-year or per kilowatt-year that obtains in Scandinavia. In his remarks he stated that there were many cases over there where the cost of imported coal was such that hydro-electric plant was not warranted. It would be very difficult, however, for steam plant to compete with so low a figure as £7 10s. per electrical horse-power installed, unless the cost of transmission in Sweden is unnecessarily high. Some twenty years ago, as a junior, I was sent over to Stockholm to lay the first system of mains in that city, and when I remember the small station at that time, and then the larger station I saw last year in the same city, marking a very great stride forward in the development of electricity, and now the construction of 25,000-H.P. or bigger hydro-electric power stations similar to what is to be adopted for transmission of energy to Stockholm for future requirements, it shows what enormous strides this industry has made during the last twenty years. I think Sweden and Norway, with about 8,000,000 H.P. available from water-power, are two very favoured countries. I would like to ask the author finally whether that horse-power is rated upon the drought rating, or whether it is taken upon the average rainfall for the year. Mr. Snell.

Mr. G. STJERNBERG: It is stated in the paper that there is very little coal in Sweden. If this source of energy has been denied to that country, there is plenty in water-power. If 8,000,000 H.P. be taken as the average power available in Sweden and Norway together, it represents a matter of 8,000 tons of coal per hour, or about 200,000 tons of coal a day. That corresponds to the output of the largest coalfields in Europe, and certainly if the energy is there means will be found to utilise it, although it is now found that in certain places the cost per horse-power installed is so high that it does not even compare favourably with the cost in the case of steam driving. Looking at the map of Sweden, one sees a great number of rivers running down practically perpendicular to the line of maximum extent of the country. In these rivers are tremendous lakes, most suitable for water storage and such purposes. There are the waterfalls, and close by are great deposits of iron ore and minerals of various descriptions. Amongst the electrical points mentioned in the paper, I should like to draw attention to the question of regulation. In the figures given on page 454 for the regulation of one of these generators it is stated that on a non-inductive load the inherent regulation is 1·5 per cent. for unity power factor and 6·3 for power factor 0·8. Those Mr. Stjernberg.

Mr. Stjernberg.

are very low figures. Speaking theoretically, it would be possible to obtain any figure for regulation if one makes the machines large enough. Another way of doing it would be to design them in such a manner as to keep the synchronous reactance as low as possible, but in any case I should not think it would be desirable to have machines of this description for supplying transmission lines. The short circuits would be too severe. The lightning arresters for a large overhead system must be set in such a manner that they can take very large amounts of energy, amounting in certain circumstances pretty nearly to a short circuit. The short-circuit current on these machines would be unusually large. It would be interesting to know if any tests have been taken. If the regulation were somewhat greater the effects of short circuit would be less severe, and by applying automatic regulators the voltage can, for purposes of supply, be kept as nearly constant as may be required for any purpose. Automatic regulators, although they may act very quickly, are not instantaneous. I notice that the author mentioned that they have had no troubles with short circuits on the water installations in Sweden. When I passed through Sweden last year I was told they had in some places provided choking coils for the express purpose of reducing the effect of short circuits. I should imagine, therefore, they have had some adverse experience, and after all, even for 50 periods, such speeds as 300 revs. per minute and more for sets of 2,000 or 3,000 k.w., are so high that one would expect to have some trouble of this description. With reference to the transformer shown in Fig. 8, it is quite true that the oil at the top of the transformer will be hottest, but if the cooling ribs be arranged in the manner indicated one would imagine that although it may cool the oil very well, it would not tend to produce a good circulation in the transformer. I notice also that these cooling ribs were made of riveted wrought-iron sheets, and I think the author told us they were very thin. In the circumstances it might be very difficult to keep them completely tight. I believe it is hardly possible to do this in riveting thin plates.

Mr. Brazil.

Mr. H. Brazil: As regards the electrical side of the paper, and particularly in connection with the means employed for protecting the overhead line from lightning discharges or other sources of over-tension, I should be glad if Mr. Clayton would tell me if the neutral-point of the Graninge system is earthed. [Mr. Clayton: It is not.] This being the case, I would point out that the arrangement of the arrester horns as described on page 459 of the paper is not very satisfactory, and will require double the pressure to cause the horns to spark when the system is entirely insulated that it will when one pole is earthed.

I should like to describe a system of connections devised and patented by Mr. H. Cooch and myself, which entirely gets over this difficulty. I would preface my remarks with the statement that all that follows refers only to 3-phase systems with the neutral-point insulated. In the diagrams herewith, H indicates the arrester horn,

Mr. Brazil.

and R the resistance for limiting the current which flows to earth. Fig. A shows, diagrammatically, the connection of horns and resistances commonly employed, and the arrangement of the horns at Graninge, as described by Mr. Clayton, comes under this category. It is true that he mentions a second horn which is in parallel with the resistance, but this, I take it, is only to provide for lightning strokes, and does not alter the principle of the arrangement. Assuming that there is no earth on the system, the excess pressure will have to be sufficient to cause two horns in series to spark before relief is given, but when an earth occurs on any pole, the spark-gap connected to that pole is short-circuited, and therefore the excess pressure that is required is only that necessary to break down one horn. Assuming, in the case of Graninge, that the horns are set so that a rise of 50 per cent. above normal will cause them to spark, each horn has to be set at 60,000 volts, and therefore when there is no fault on the system,

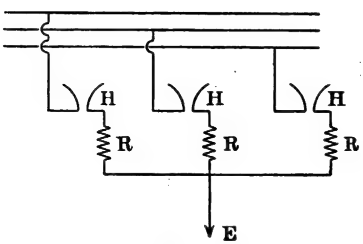


Fig. A.

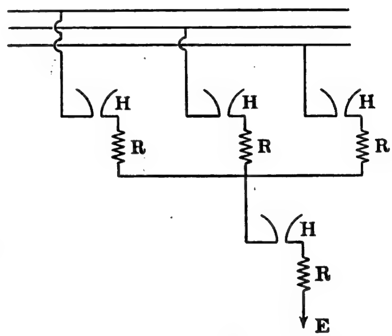


Fig. B.

120,000 volts, *i.e.*, three times the normal pressure, will have to exist between phases before relief is given. Fig. B shows an alternative arrangement in which an attempt has been made to overcome this difficulty by inserting a fourth horn and resistance between the common terminal of the three resistances R R R and earth. In this way there must be always two spark-gaps in series between any two phases or between any one phase and earth, so that, theoretically, the same excess pressure will cause the spark-gaps to discharge, whether all three phases are equally insulated, or one phase is earthed. It has been found, however, by experiment, that this arrangement does not provide equal protection under different circumstances. For example, in a 6,000-volt 3-phase system, it was found that the pressure required to produce a discharge when all three phases were equally insulated was 4,000 volts higher than when one phase was earthed. This difference is due to the unequal distribution of potential across the two horns (which are in series) when one pole is earthed. If we have two horns in series, each of which is set individually to spark at 5,000 volts, and place these across the terminals of a system one pole

Mr. Brazil. of which is earthed, we may get 5,000 volts across the horn which is connected to the non-earthed terminal, and only 2,000 across the other, and, of course, as soon as the first horn breaks down, the second one has the full potential of the system on it, and breaks down also.

This unequal distribution of potential between the two horns appears to be due to the capacity of the metal connections forming the common terminal of the three resistances R R R, and we neutralise this capacity, and thus render this point a stable one, by connecting it to the neutral point of a choking coil, or the high-tension winding of a transformer which is connected to the same source of supply as the arrester horns. This arrangement is shown in Fig. C, and whether the system is perfectly insulated, or whether one pole is earthed, makes no difference to the voltage at which the arresters will spark. In Figs. A and B, as I have before mentioned, it is necessary to set the horns to provide for the condition when one pole is earthed, and therefore when

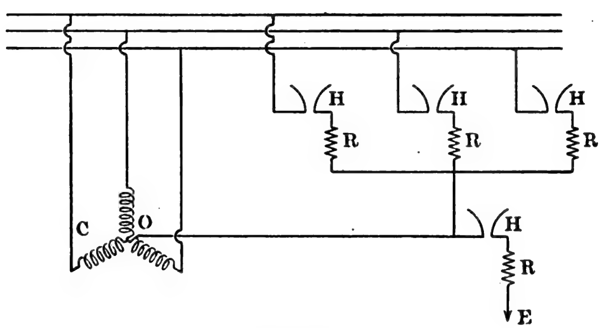


FIG. C.

all three poles are insulated (which I take it would be the normal condition), there is very little, if any, protection provided for rises due to surges or resonance. With the arrangement as shown in Fig. C, this difficulty disappears, and I venture to suggest that this device will be found of considerable use to those engineers who have a system with the neutral-point insulated.

The resistances used in connection with the lightning arresters are very important, and it is generally agreed that many of the troubles experienced with lightning arrester apparatus have been due to the resistances being of insufficient capacity to withstand the heavy load which is thrown on them when a discharge occurs. The problem of designing a suitable resistance is a peculiar one, in that it is required to have a very high ohmic value, and at the same time the capacity for absorbing very heavy loads for a short period. Having had a considerable amount of experience with the water and carbon type of resistance, I venture to disagree with the author's conclusion that a water resistance is the best. I should be prepared to agree with him if by carbon resistances he meant only the carbon rod or other compressed

Mr. Brazil.

carbon type, but would suggest that there are other types of carbon resistance, which, at any rate to my mind, are much to be preferred to the water type. The failures with the carbon rod type are nearly always due to the fact that it is very difficult to get a uniform resistance per unit length, and when a number are in series, it is more than likely that one of them has a high resistance point or a crack in it. When a discharge occurs, a very large proportion of the available potential is concentrated at this point, the rod gets hot and breaks, and the whole resistance is useless. The remedy I would suggest for this state of affairs is certainly somewhat drastic, and would appear to be rather paradoxical. It is to take the carbon rods and to break them into thousands of pieces, distributing these pieces in a suitably shaped groove. The resistance then consists mainly of bad contacts. To take a medical analogy, the disease from which the carbon rods are suffering is bad contact, and we inoculate for this disease to such an extent that we may be quite sure it will be immune from this trouble in the future. This disintegration of the carbon rods is practically what is done in the carbon powder resistances to which I would draw attention.

You will see on the table a resistance unit which consists of a fire-clay slab 12 in. square by $1\frac{1}{2}$ in. thick, with a zigzag groove $\frac{3}{4}$ in. deep and $\frac{5}{8}$ in. in width moulded in it. In this groove is placed a special kind of carbon powder, and it will be noticed that the grooves themselves are not parallel to one another, the object being to provide a thickness of insulation at each point which bears some relation to the potential between one leg and another at that point. Now, as to the capabilities of this resistance, I should have been glad if the author had given us some idea of the size of the water resistances and the power they would absorb, and for how long. Perhaps he will be good enough in his reply to give these particulars so that a comparison may be made. To that end I give figures of the capacity of the resistance I have been describing. With a voltage of 6,000 across the terminals the current rose to a maximum of 1·9 amperes in just over 2 minutes, and then slowly decreased to 1·35, at which figure it remained even after the lapse of 8 minutes. The maximum power absorbed in this case is 11·4 k.w., and when steadied down is 8·1 k.w. With 10,000 volts across the terminals the current rose to a maximum of 2·4 amperes, and then decreased to 1·8 at the end of 1 minute, when the resistance was switched off. The maximum load in this case was 24·2 k.w. The above tests are, of course, very severe, and it is highly improbable that the resistance would be subjected to them in practice. The object in giving these figures is to show that even under the worst conditions the resistance will keep the current within safe limits. I do not wish to be understood to say that the resistance subjected to the severe tests I have mentioned would, when allowed to cool, give the same figures if tested again, but if when cool the powder is mixed and redistributed, the results will be the same as I have given, thus showing that the powder is unchanged, although it has been at a good red heat

Mr. Brazil. for some considerable time. This property that these resistances possess of absorbing, without injury to themselves, large amounts of power for short periods, is, of course, due to the very large range of temperature permissible, and the indestructibility of the materials employed. As mentioned before, I have had a very considerable amount of experience with water resistances, and my objections to them are as follows: (1) They introduce moisture into the E.H.T. chamber; (2) they will vary in resistance to a very great extent with the ordinary temperatures obtaining in sub-stations; (3) the possible range of temperature, and therefore the capability of absorbing power for any length of time, is very limited; (4) a very small quantity of impurity getting into the water will alter the resistance value to an enormous extent; (5) if subjected to severe cold they will freeze.

I now turn to the permanent leak arrester, and am pleased to be able to agree with Mr. Clayton that this is a very valuable piece of apparatus. I have had no personal experience of the water-jet type, but should imagine that it requires a good deal of attention, as the value of the resistance varies considerably, especially if anything gets into the water. I take it that all engineers, if they could obtain a dry resistance which costs no more and is as efficient, would install it in preference to the water type, and I wish to suggest such a resistance which is similar to the one I have described. This resistance consists of a number of insulating slabs 12 in. square, made of material more nearly resembling porcelain than fire-clay, having a much larger number of parallel grooves about $\frac{1}{4}$ in. wide. These grooves are filled with a very high resistance powder, and the slabs are stacked one on top of the other and connected in series. There is no difficulty in getting 1,000 ohms per inch run of the groove, and with 100 in., such as may be got on a slab of the size mentioned, there will be 100,000 ohms on one slab. Taking the pressure as 40,000 volts, the figure the author mentions, the neutral-point not being earthed, it will be necessary to allow for 40,000 volts across each resistance when one pole goes to earth. With 100,000 ohms on each slab, twenty of those slabs will be required in each phase, and these will form a resistance which will pass one-fiftieth of an ampere when one pole is earthed, and $\frac{1}{85}$ of an ampere when all the poles are insulated. I think that would make a very satisfactory permanent leak arrangement. The author has told us that he is never sure what he will get with the water-jet arrangement, as the quality of the water varies so enormously, whereas these resistances can, I think, be looked upon as having a fixed value; they can be designed to meet special requirements, and they will remain without any appreciable alteration.

Mr. Patchell. Mr. W. H. PATCHELL: I am sure the author need not have gone to Scandinavia to get the two forms of apparatus which are mentioned on page 443. Twenty-five years ago, or thereabouts, I saw tilt hammers working in the iron works in South Yorkshire, and to-day you can find rod transmissions working practically by the mile in Cornwall among the mines there; and, as Mr. Mordey remarks, in the Isle of Man too.

Mr. Patchell.

Sometimes where the pull is all in one direction ropes are used, but the wooden rods are more general, and are known in that part of the world as flat rods; in fact, such is the prejudice of the Cornishman for flat rods that last November I plead guilty to having had to set up some myself, which are working very satisfactorily, and we do not get any short circuits on them. The civil engineering side of this paper is extremely interesting. I think the man who put an arch on its side for a dam was a plucky one, but I do not find in the paper how he got a watertight joint on the upstream or the downstream side. The pressure on the upstream side is greater, but the scour on the downstream side is a far worse enemy to dam construction than the pressure on the upstream side. The author does not mention whether the water leak resistances are put on when they see a thunderstorm coming, as I find they are in North Italy, or whether the water is left on all the year round. Looking at the first figure of the water-jet resistance I was struck with the apparently great gap between the line and earth, and the comparatively small gap between the phases. If I understood the photograph aright, the tank from which each of the three phases was supplied by a jet was common to all, and seemed to be very close to the phase connections. On the question of transformers, if single-phase transformers are put into single tanks this simplifies the question of tank making very considerably. Mr. Stjernberg mentioned quite rightly that the design shown did not favour the best possible oil circulation. It seemed to produce excellent cooling at the top, but I did not quite see how the cold oil could thoroughly circulate down to the bottom. If we have to go to Sweden to learn how to make transformers, it is good to see that they have to come to England to learn how to make the cases, for without the cases the transformers will not work. On the question of governors, the turbine governor shown on the screen reminded me very much of a governor in use on a water-power system in America some years ago. Any amount of care was taken with everything except the governor, in which the whole life of the supply depends on an inch belt running on a pulley without flanges. That did not appeal to me as being sound engineering. Then with regard to the figure of one of the dynamos which was marked with Mr. Clayton's name—on which we congratulate him—and described as having a pole-ring with the arms and the boss all cast together, the figure was very clear, but it did not show that the boss was split. Is it not very risky and a considerable trouble to get a casting of this type cooled without tearing the arms from the boss? My experience in an iron foundry would not lead me to adopt that type. There was another interesting photograph referring to the cradles which are put underneath the wires where the wires cross railroads and public roads. We have the same regulation in this country, and up till lately, perhaps up till now, the same regulation has obtained in America. There has been a conference there lately, of which I have been told within the last ten days, where the railway men met the electrical men. One of the electrical men had the pluck to carry the war into the enemy's country.

Mr. Patchell.

He said, "You call for a cradle underneath our wires where we cross your line?" "Yes," they replied, "certainly." "Then," he said, "we call for a cradle underneath your bridges where your bridges cross our lines. Is that any more ridiculous? Why should not we make our electrical lines stranded and sufficiently strong to hold up over your bridges or over your railway lines? You have slips, just as sometimes we have slips." The result of that was that it has been agreed to put the money into better work in the lines and do away with the cradles, and my experience leads me to believe they will have a much sounder job. There is only one other point I wish to mention. Mr. Stjernberg tells me that Sweden is a very cheap place to travel in. We have seen to-night that the country which gave us John Ericsson has a great deal of high engineering interest to show to those who have time to visit it.

Mr. Clayton.

Mr. A. V. CLAYTON (*in reply*): Mr. Snell, in criticising my paper, mentioned the cost of the installation as £17 10s. per electrical horse-power. I would like to make one little correction in regard to that. It is not per electrical horse-power; it is really per turbine horse-power. Mr. Snell asked what would be the price per horse-power obtained in Sweden. That is a very variable quantity. In some cases it goes down as low as 25 kroners, which would be about 27s. 6d. per horse-power-year, and it runs up as high as 120 kroners, but I should think the fair average would be somewhere about 50 kroners (about 55s. per horse-power-year), and they are entitled to employ the power 24 hours per day so long as the water lasts. The usual proviso in the contracts is that in case of shortage of water the supply company is not compelled to deliver the full quantity of power, but in some cases, say in contracts which are made for a number of years at such a high price as £6 10s. per horse-power per year, the company guarantee to supply the full quantity. In a power station the contracts for supply of power are usually divided up. Supposing a power station has 20,000 H.P. available; they will sell their first 7,000 H.P., or whatever it may be which they have constantly, at their highest price, and will guarantee delivery. Then comes the next lot of customers which have only a day-load, we will say, where the water-power can be stored up during the night. Then finally come those who have the overflow power. In the last category would come such an industry, for instance, as wood pulping, where power can be taken at any moment of the day. The manager of the wood-pulping works simply telephones through, and if the power company has a couple of thousand horse-power available, they can take it up. They can take up the power at any instant; they do not require any notice at all. In a big wood-pulping mill the number of hands required to work the mill for pulping alone would not be more than about ten, and those men can be used as labourers for carting or shifting lumber when the power is not available. When the power is available the men are called in, and they start pulping, so that there is no loss in letting the mill stand idle, apart from the loss of profit, interest on capital charges, etc. Mr.

Snell also accused me of making a statement which I really did not make, or at least I did not intend to make. He said I stated that in many cases in Sweden electrical power obtained from imported coal was cheaper than electrical power obtained from water-power. I did not state that specifically with regard to Sweden. Mr. Clayton.

Mr. SNELL: That may be my mistake. Mr. Snell.

Mr. CLAYTON: I did not state "in Sweden"; I was not thinking of Sweden, but of somewhere else. I stated there were many cases projected or actually building, but I did not intend to convey that they were in Sweden. The 8,000,000 water-horse-power which it is computed is available in Scandinavia has been arrived at from a computation of the rainfall. The subject is fully dealt with in a paper under the title of, "Les chutes d'eau Scandinaves et leur avenir," which my colleague Lieutenant Lubeck contributed some few years ago in "La Houille Blanche," and I shall have great pleasure in sending a copy of it to Mr. Snell. It is computed on the average rainfall over, I think, 25 or 30 years, and the land and sea-levels. Mr. Stjernberg discussed the question of the regulation of the generator described in the paper. The regulation is given as having 1·5 per cent. regulation for unity power factor, and 6·3 per cent. for a power factor of 0·8. As I stated in the paper, those are very exceptional figures. More average figures would be about 7 and 16, or 8 and 20. But I would like to explain that that regulation is voltage rise, it is not voltage drop, and it has been brought about in a rather artificial manner; that is to say, as I have explained, the entire ring and the poles are cast of steel all in one piece, and the flux density in that is driven up to an extraordinarily high figure, so that the top of the magnetisation curve on which the generator is working is practically the flat half of a steel curve. The air-gap is reduced to the smallest amount practicable for mechanical considerations; there are partially closed slots, that is to say, the slit in them is not more than about 2 mm. and the air-gap in a generator of that size is about 4 to 5 mm. The ampere-turns in the field are very large, and are distributed mainly in the steel part. That accounts for the extraordinarily high figures of regulation. Further, these figures of regulation were not compiled by me, they were compiled from the official tests by the consulting engineers who tested the plant—the Pröfnings Anstalten, which is the recognised testing body of Scandinavia. The temperature rise of the generator was the maximum allowed, about 40° C. I quite agree with what Mr. Stjernberg said about the short-circuit current being large, and I would myself, given a free hand in designing a generating station, most certainly be an advocate of having generators with large impedance and using auto-regulators. I am sorry to say that auto-regulators have not as yet made the progress in Sweden they ought to have done, but I think they are making better progress now. As regards using choking coils to introduce larger impedance and check the flow of current on short circuits, I think Mr. Stjernberg is incorrect. I speak generally in my paper of the practice in Sweden,

Mr. Clayton. and I do not think you will find that what he says is the case generally. I do not know of a single instance—and I know most of the power stations—where impedance coils (choking coils) have been introduced for that purpose. They are put in between the generators or the transformers and the horn lightning-arresters, with the idea of checking the lightning discharges into the station. That is a very usual though old-fashioned course, and I do not know what the exact good of the arrangement is with the primitive coils often used, but I do not think that anywhere they are employed for the purpose Mr. Stjernberg said. If so, it is an isolated case. Finally, there was the question of the circulation of the oil in the oil-cooled transformer boxes. That is a very troublesome thing, but careful tests were made on these boxes to see what the difference of temperature of the oil was in various parts of the box. Tests were made on different boxes, both with the transformers in the boxes and the transformers out of the boxes; temperature search resistances were immersed at various points, and the circulation of oil by that means was proved to be very good indeed. The 3-phase transformers had the three cores placed in the position of an equilateral triangle. The yoke at the top was open, which allowed for a rush of oil from the part of highest temperature, and a circulation down the side of the boxes to the bottom. It was found that the circulation was exceedingly good; the oil used was very thin, not at all like the type of oil used in many of the American transformers, where the usual thick oil is used. Moreover, while on the question of oil, I may mention it was found that the thinner oils as a rule gave better insulation resistance than the thicker oils. Then Mr. Brazil made some remarks about the earthing devices, on which I am to a large extent in agreement with him. Of course any dry resistance would be much better than a water resistance. A number of very competent engineers and assistants have carried out experiments on that point, and they have discarded carbon chiefly because of its inequalities, and, moreover, it still seems to be in the experimental stage. As Mr. Brazil explained so very clearly, he uses carbon dust. I should like to ask Mr. Brazil one question with regard to that, and that is, whether he does not find that trouble may occur in practice owing to the carbon dust becoming more or less packed, and so altering the resistance. As to the capacity of water resistances, I am not able to speak from memory, but in a general way I can say that these lightning-arrester resistances are merely required momentarily. I have seen several lightning discharges, or atmospheric discharges, taking place with about ten-minute intervals, and there has been no trouble with the water resistances in large power stations of 5,000 to 10,000-k.w. capacity. They are made of very large dimensions, and on the whole have been found more dependable than carbon. It may be that a suitable class of carbon has not been used. With regard to troubles arising from freezing, the lightning only occurs in the summer-time; it is not prevalent in the winter. Mr. Patchell remarked that in Italy they couple these protective

devices in when they expect lightning storms to come on, but they do not go as far as that in Sweden. They put on these protecting devices in the summer-time when lightning is about, and in the winter-time, when there is no lightning, they take them off. As to using carbon resistances for the earthing devices, they have also been tried. The trouble about that, however, was that damp sometimes got into the carbons, and due to that or other causes, they cracked. In other words, this comes under the heading of carbon being unequal in quality, subject to changes, and generally unreliable. Mr. Clayton.

Mr. BRAZIL: I think I stated that I did not like carbon rod resistances at all. It was only powder that I was dealing with. Mr. Brazil.

Mr. CLAYTON: We are in agreement. Reference was made by Mr. Patchell to the arched part of the dam at Gullspång, and the method employed for making it tight. The dam was faced off with fine cement, and the bottom caulked with stamped yellow clay. At the back there was a protection of wooden beams, and the wearing surface was faced with stone; and so far there does not seem to be any trouble. Mr. Clayton.

Mr. PATCHELL: No concrete apron, only timber? Mr. Patchell.

Mr. CLAYTON: Only timber. As regards the distance between the phases of the water resistances, the slide did not show that there were dividing slabs between the phases. Each one is in a chamber itself. As regards the oil circulation of the transformer boxes, I think I have previously replied to that question in dealing with Mr. Stjernberg's criticisms. One other point that Mr. Patchell referred to was the casting of the boss-arms and ring of the generator magnet-wheel all in one. The qualities of cast iron and cast steel are quite different. In iron, of course, you would not attempt to do such a thing, but the qualities of steel are quite different in that respect. When steel is first cast it is an exceedingly brittle material—worse than iron almost; but the process of annealing takes away this brittleness and all the stresses which are due to the casting shrinkage. As regards the rail crossings, there is a very strong feeling in Sweden that they are unnecessarily costly. The people would instead prefer to have the money spent in footbridges over the rails, and dispense with these very expensive electrical crossings. Mr. Clayton.

The PRESIDENT: I now ask you to give a hearty vote of thanks to Mr. Clayton for his most interesting paper, which has led to such a useful discussion. The President.

The meeting adjourned at 9.46 p.m.

COMMUTATION PHENOMENA AND MAGNETIC OSCILLATIONS OCCURRING IN DIRECT-CURRENT MACHINES.

By G. W. WORRALL, M.Sc., Associate Member.

(*Paper received January* 5, *and read at Birmingham on April* 27, 1910.)

INTRODUCTION.

The experiments described in this paper were undertaken as an extension to direct-current machinery of the investigations upon alternators which the author had previously been engaged upon.*

The magnetic oscillations were observed by means of E.M.F.'s induced in search coils placed on the machine parts in such positions as to link the oscillating flux. The E.M.F. waves were photographically recorded by means of a Duddell high-frequency oscillograph and revolving drum camera. The machine employed in the investigation was a 2-pole generator with adjustable commutating poles; the brushes were of carbon and of a width equal to one commutator segment plus insulation.

The principal details and conditions of running of the machine are given below, and a diagram is shown in Fig. 1. These conditions were maintained throughout all the experiments, except where stated to the contrary:

Potential difference on load, 80 volts; current, 20 amperes; speed, 750 revs. per minute; exciting current, 1 ampere; normal commutating pole current, 5 amperes.
Brushes in geometrical neutral plane.
Diameter of armature, 25 cms.
Length of armature iron, 15 cms.
Number of conductors, 270.
Each conductor formed of 4 wires in parallel.
Turns per coil, 3.
Coils per slot, 2.
Number of slots, 45.
Winding step measured in coil sides: forward, 45; backward, 43.
Diameter of commutator, 15·8 cms.
Number of segments, 45.

* *Journal of the Institution of Electrical Engineers*, vol. 37, vol. 39, vol. 40.

Average current density in brush contact surface; 5 amperes per square centimetre.
Kind of carbon used, le carbone "z."
Air-gap of main poles, 2 mm.
Air-gap of commutating poles, 2 mm.
Commutating pole arc, 43 mm.
Length of commutating pole, 15 cms.
Shape of slot, open.
Width of slot, 7·5 mm.
Depth of slot, 22 mm.
Width of tooth top, 10 mm.
Number of turns on each main pole, 3,000.
Number of turns on each commutating pole, 200.

Search coils were placed on the pole system and armature as shown in Figs. 1 and 2:—

Coil 1 P	...	15 turns.	Coil 8 P	...	60 turns.
„ 2 P	...	5 „	„ 9 P	...	20 „
„ 3 P	...	5 „	„ 1 A	...	1 „
„ 4 P	...	15 „	„ 2 A	...	10 „
„ 5 P	...	15 „	„ 3 A	...	30 „
„ 6 P	...	60 „	„ 4 A	...	2 „
„ 7 P	...	60 „			

The oscillograph camera drum was driven by a small electric motor with series and shunt-regulating resistances. A four-sided rotating mirror was driven from the drum shaft by belt and pulleys in the ratio 1 : 2. The speed of the system could be readily adjusted to synchronism with the machine under investigation, and the oscillations could therefore be conveniently studied in the mirror before taking a photographic record.

The drum speed was at a known value when the mirror was at synchronism, and it was therefore unnecessary to measure the speed. The oscillograph was calibrated by inserting a known E.M.F. in the circuit; this was done immediately after taking each record, and where the records consisted only of high-frequency oscillations, without stopping the machine, the oscillatory current being damped out by means of a high inductance. Thus on each record a photographic line was drawn parallel to the zero line and at a distance from it corresponding to the known E.M.F. The analysis of the oscillations recorded was only possible by the accurate knowledge of the position of the armature corresponding to a point on the oscillograph record. This was obtained by means of a contact maker placed on the shaft of the machine and connected up to the oscillograph in the way devised by the author for the previous researches. During the instant of contact the oscillograph was shunted by a small accumulator, thereby producing a momentary current and hence an isolated peak in the record

which was being taken. This peak corresponded to a predetermined position of the armature. The contact maker was in all cases set at the

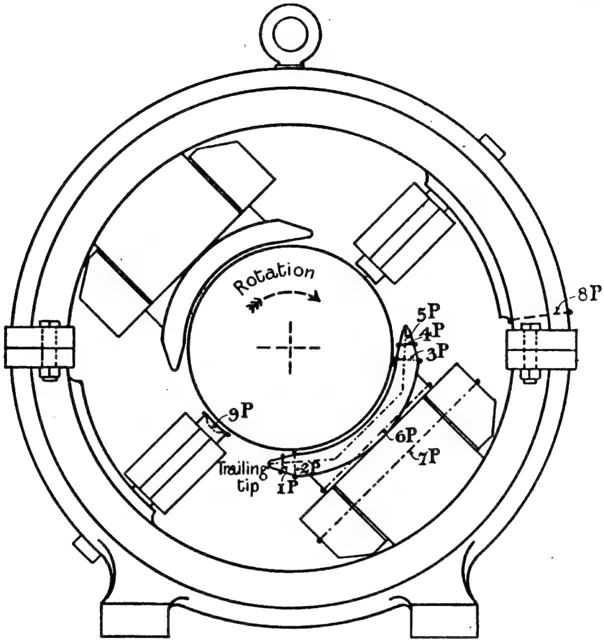


FIG. 1.—Diagram of Machine.

beginning of short circuit by the negative brush. A diagram of the oscillograph circuit is given in Fig. 3. The frequency of the oscillation

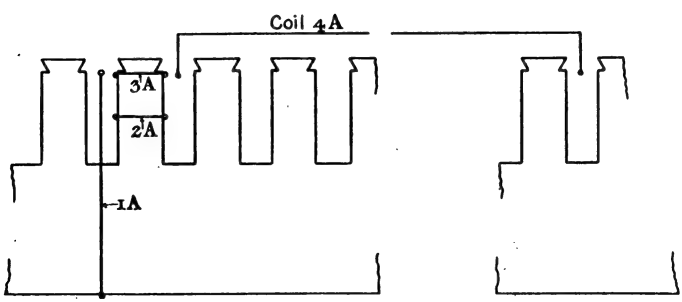


FIG. 2.—Position of Coils on Armature.

was determined from the time scale of the record. Many of the results obtained in the author's previous researches on alternators are

also applicable to direct-current machines, and the present investigations do not include these.

The contact maker employed was that described by Arnold in "Die Gleichstrommaschine" vol. 1, and as no description appears to have been published in England a translation is, with the kind permission of Professor Arnold, given below :—

"The construction of the contact maker is shown in Figs. 4 and 5. The contact is not of the rubbing type but of the pressure type, and the duration of contact is so short that the apparatus works well even with alternating current of high frequency. The apparatus consists of a contact disc S rigidly coupled to the machine shaft, a graduated disc T, and a movable ebonite piece G. On G are mounted, insulated from each

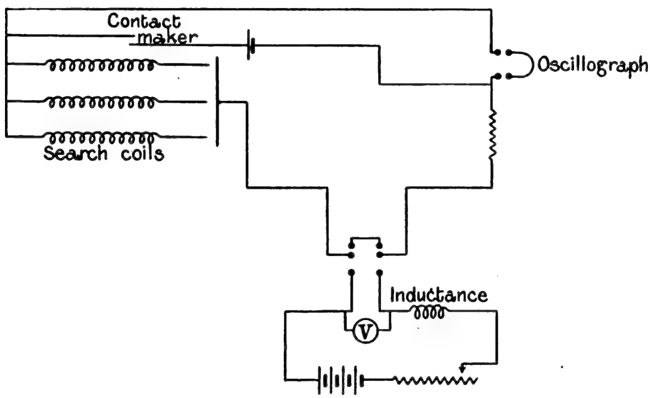


Fig. 3.—Oscillograph Circuit.

other, the two contact springs f_1 and f_3 and the opposing springs f_2 and f_4. On S is mounted a raised steel piece n_1. G is rotated to any desired position relative to n_1 and clamped by the screw *s*. The finger *z* serves to read the position of G.

"The current circuit through the conductors *a* and *b* is closed once in each revolution when n_1 comes under f_1; f_1 is thereby raised until it comes into contact with the contact surface k_1 of the spring f_3. But the contact continues only for an instant, for in the next instant the springs f_1 and f_3 are together raised and break the contact at K_2 on which f_3 rests. In order that contact shall not be made again after n_1 has passed there is a second piece n_2 displaced axially and radially to *n* which raises f_3 and holds it up until f_1 returns to its original position.

"The contact maker was devised by G. Schade, the mechanic of the Electrotechnical Institute at Karlsruhe. The Physical-mechanical Institute of Dr. Th. Edelmann at Munich has undertaken its manufacture."

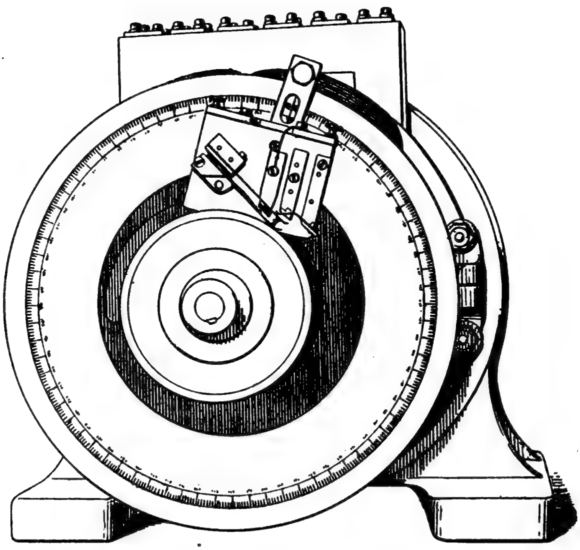


FIG. 4.—Contact Maker.

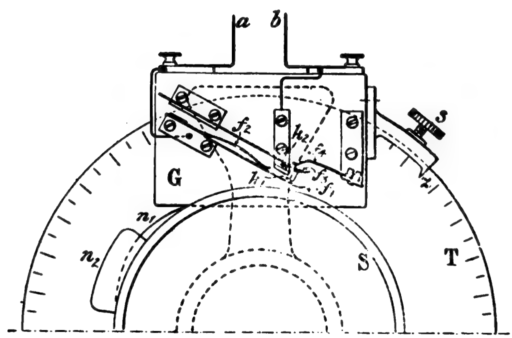


FIG. 5.—Contact Maker.

The contact maker was found to be absolutely certain and accurate; the duration of contact was, at the normal speed of the machine, considerably less than $\frac{1}{10000}$ part of a second.

The magnetic oscillations occurring are due to two main causes :—

1. The movement of the armature teeth in the magnetic field.
2. The commutation of the armature current in the short-circuited coil.

The first class of oscillation was fully dealt with in the previous papers on alternators above referred to, and since the results then obtained apply equally to direct-current machines, these oscillations were not further investigated except where they were associated with oscillations of the second class, or where a difference in the design of the machines employed gave rise to the existence of oscillations not previously investigated. The oscillations of the second class were found to be far more important, and in most parts of the machine greater in magnitude than those of the first class. These oscillations were due to the change of current in the short-circuited coils, and since there were two such coils there were two sets of oscillations which were displaced relatively to each other 180°, owing to the number of commutator segments being odd.

Although the currents in the two coils changed in relatively opposite directions, the position of one coil was the reverse of that of the other, and hence the magnetic oscillations produced were in the same direction. Thus the number of oscillations occurring in a revolution of the machine was twice that of the commutator segments.

The coil at the instant of short circuit was opposite to a pole-piece and linked the main flux, hence the magnetic oscillation caused a pulsation in the main magnetic circuit which could be readily observed by means of the search coil 5 P wrapped round the pole-shoe.

The nature of the magnetic oscillation depends upon the nature of the commutation taking place, and since the flux at each instant is proportional to the current in the short-circuited coil, the E.M.F. induced in a search coil linking the flux forms a picture of the commutation taking place. Such a picture of commutation was found to be a most accurate and sensitive guide to the general behaviour of the machine, inasmuch as its production was continuous and did not interfere with any of the working parts.

The usual method of commutation research is to measure the short-circuit current directly by means of a resistance inserted in an armature coil, but this method only gives results for two adjacent segments and the coil between them, and gives no indication of the nature of the commutation taking place at other points of the commutator. Such results are liable to be very misleading, for the experimenter cannot be sure that the brush is making good and uniform contact, but a record of the commutation taking place over the whole circumference of the commutator forms a reliable guide. The resistance inserted in the armature coil generally requires to be greater than the resistance of the coil itself, and is liable to influence the results obtained, and in any case there is nothing to show what influence the resistance has.

The method adopted in this research is free from all such objections, and by its means many interesting and important phenomena have been brought to light. Before proceeding to describe these, however, commutation will be considered from a theoretical point of view, and several results practically obtained in the research will be shown to be theoretically possible.

PART I.—COMMUTATION PHENOMENA.

SECTION I.—THEORY OF COMMUTATION.

The theory of commutation has been the subject of very considerable discussion in recent years. On the one side it is stated that commutation should take place in a neutral field, while on the other it is stated that commutation should take place in a commutating field.

The first statement is based on the assumption that the short-circuited coil should possess no self-induction, while the second assumes that the self-induction E.M.F. exists but is compensated by a commutating E.M.F. Both sides are agreed that no E.M.F. should exist in the coil during commutation, but they differ in the conditions necessary to effect it. The resultant field to which the coil side is subject consists of two main components: one due to the self-induction of the coil, in which is included all mutual inductive effects of neighbouring coils, and the other due to the main and commutating poles, if any, and the main armature reaction. The former may be termed the internal component, and the latter the external component. The internal component is approximately perpendicular to the plane of the coil, and the external component is approximately parallel therewith.

If the resultant field to which the coil side is subject be neutral, it must either be zero in magnitude or the perpendicular velocity of the coil side relative thereto must be zero. By perpendicular velocity is meant the velocity component of the coil side perpendicular to the line of action of the field. The former condition is impossible because the two components are approximately perpendicular to each other, but the latter condition may exist; hence the self-induction of the short-circuited coil cannot be said to be non-existent by virtue of the cancellation of its field, but by virtue of the cancellation of the perpendicular velocity of the coil side relative to the resultant field.

The commutating E.M.F. is generated by the external component of the resultant field, which therefore is the commutating field. If the commutating E.M.F. be equal and opposite to the self-induction E.M.F., the magnitudes of the fields generating them are in inverse proportion to the perpendicular velocities of the coil side relative thereto; and further, the direction of action of one component coincides with the direction of velocity of the other, and *vice versâ*. From this it follows that the direction of the resultant perpendicular

velocity of the coil side coincides with the direction of action of the resultant field. Hence the coil side possesses no perpendicular velocity relative to the resultant field.

Thus both lines of reasoning lead to the same result, and the apparent diversity of opinion is merely due to different methods of expression. The conditions for good commutation above given cannot hold in practice during the whole of the commutation period, but only during the final instant. It is, however, generally possible to obtain satisfactory commutation without compensating or rendering non-existent the self-induction E.M.F. of the coil. This may be effected by a proper choice and disposition of the contact resistance of the brush.

The choice of the resistance has already been studied by many investigators, but few have dealt with its disposition. The use of a carbon tip to a copper brush, and Kapp's patent, in which the resistance of the forward tip of the brush is increased by means of holes in the

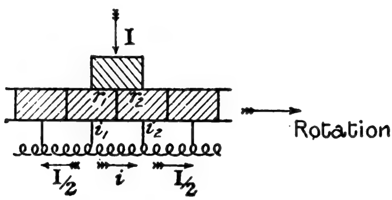


FIG. 6.

contact surface are attempts in this direction, but the proper disposition of the resistance over the contact surface may be carried much further than this.

Consider a brush of width equal to one segment, and for the sake of simplicity let the insulation between the segments be infinitely thin. Assume that commutation is to follow the straight-line law.

Let—

L = self-induction of the coil as above defined.
i_1 = current flowing through the rear segment (instantaneous value).
i_2 = current flowing through the forward segment (instantaneous value).
i = current flowing through short-circuited coil (instantaneous value).
r_1 = resistance of contact to rear segment.
r_2 = resistance of contact to forward segment.
I = current flowing into brush.
t = time after commencement of short circuit at which the above values occur.

Then the difference of potential existing between the ends of the short-circuited coil is equal to the difference between the potential

drops across the two contact surfaces, and this must equal the self-induction E.M.F. (Fig. 6);

i.e.—

$$L \frac{di}{dt} = r_2 i_2 - r_1 i_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Now—

$$i_1 = I/2 + i, \quad \text{and} \quad i_2 = I/2 - i, \quad \text{and let} \quad i = \phi(t),$$

then—

$$L \frac{d}{dt} \phi(t) = r_2 \left(I/2 - \phi(t)\right) - r_1 \left(I/2 + \phi(t)\right).$$

Let—

a = total surface of brush.
s = contact resistance per square millimetre of surface.
x and y = contact areas over the rear and forward segments respectively.

Then—

$$r_1 = \frac{s}{x} \quad \text{and} \quad r_2 = \frac{s}{y} = \frac{s}{a-x} \quad \text{since} \quad x + y = a,$$

and—

$$L \frac{d}{dt} \phi(t) = \frac{s}{a-x} \left(I/2 - \phi(t)\right) - \frac{s}{x} \left(I/2 + \phi(t)\right),$$

or—

$$(a-x)\, x\, L \frac{d}{dt} \phi(t) = s\, x \left(I/2 - \phi(t)\right) - s(a-x)\left(I/2 + \phi(t)\right)$$

$$= I\, s \left(x - \frac{a}{2}\right) - s\, a\, \phi(t),$$

or—

$$x^2 L \phi'(t) - x\left(a L \phi'(t) - I s\right) - s\, a\, \phi(t) - I s \frac{a}{2} = 0.$$

Hence—

$$x = \frac{a L \phi'(t) - I s \pm \sqrt{\left(a L \phi'(t) - I s\right)^2 + 4 L \phi'(t) \left(s\, a\, \phi(t) + I \frac{s\, a}{2}\right)}}{2 L \phi'(t)}.$$

It is evident that the quantity under the radical is greater than $(a L \phi'(t) - I s)$, hence only the positive sign may be considered.

If—

v = the surface velocity of the commutator,
f = the width of the brush measured circumferentially,

$$\phi'(t) = \frac{I v}{f}, \quad \text{and} \quad \phi(t) = \frac{I v t}{f} - I/2,$$

when the commutation follows the straight-line law.

Then—

$$x = \frac{a\,L\frac{I\,v}{f} - I\,s + \sqrt{\left(a\,L\,I\frac{v}{f} - I\,s\right)^2 + 4\,L\frac{I\,v}{f}\left(s\,a\frac{I\,v\,t}{f}\right)}}{2\,L\frac{I\,v}{f}}$$

$$= \frac{\frac{a\,L\,v}{f} - s + \sqrt{\left(a\,L\frac{v}{f} - s\right)^2 + 4\,L\,s\,a - \frac{v^2}{f^2}t}}{2\,L\frac{v}{f}} \quad . \quad . \quad . \quad (2)$$

This equation shows the necessary variation of the contact surface over the rear segment. It is not linear, and hence an ordinary carbon will not follow such a law. If, however, the sides of the surface be curves the contact may be made to follow any law desired.

Let z be the width of the brush surface in a direction parallel to the commutator axis.

Then—

$$\int z\,v\,d\,t = x, \text{ and } z = \frac{d\,x}{d\,t}\,\frac{1}{v}.$$

Now—

$$\frac{dx}{dt} = \frac{\frac{1}{2}\cdot\frac{4\,a\,L\,v^2\,s}{f^2}}{\frac{2\,L\,v}{f}\sqrt{\frac{a\,L\,v}{f}\left(a\,L\frac{v}{f} - 2\,s + 4\frac{s\,v\,t}{f}\right) + s^2}} = z\,v,$$

or—

$$z = \frac{a\,s}{f\sqrt{\left(a\,L\frac{v}{f} - s\right)^2 + 4\,L\frac{v}{f}\left(s\,a\frac{v\,t}{f}\right)}} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

When $t = 0$, $x = 0$; if these values be substituted in equation (2), the value of a will be obtained, and—

$$a = \frac{s\,f}{L\,v}.$$

Now substituting this value of a in equation (3)—

$$z = \frac{s}{2\,L\,v}\sqrt{\frac{f}{v\,t}},$$

when $t = 0$, $z = \infty$, and when $t = f/v$, $z = \frac{s}{2\,L\,v}$. Hence the axial width of the rear tip is infinity, and that of the forward tip is $\frac{s}{2\,L\,v}$.

Fig. 7 shows the shape of the brush surface. The shape of brush obtained in this way, although not in itself practicable, points the way

to the proper disposition of the resistance over the contact surface to obtain approximately straight-line commutation.

The resistance of the contact surface over the rear segment must be very low compared with that over the forward segment, and this relation must hold not merely at the end of the period but quite early in the period. This disposition of the resistance may be approximated to by cutting away a portion of the surface of an ordinary brush as shown in Fig. 8. In this way the resistance to the forward segment is made high before, say, one-half of the short-circuit period has expired.

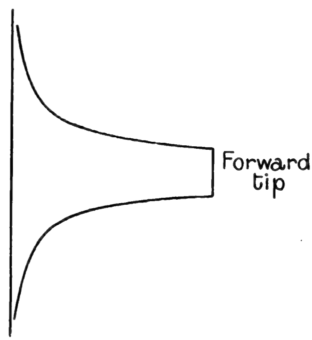


FIG. 7.

The direct effect of such a disposition of the contact resistance may be seen from equation (1). The potential difference forcing the current to change is made high during the early portion of the short-circuit period, and hence the commutation is accelerated at the beginning instead of at the end of the period. This prevents a rush of current at the final instant, and renders the current change much smoother. The magnitude and disposition of the contact resistance and the self-

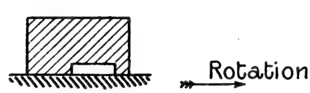


FIG. 8.

induction of the coil determine what may be called the natural period of commutation, while the mechanical design and speed of the machine determine the available period. The natural period may be defined as the time required for the current to commutate under the conditions existing in the circuit of the coil, while the available period is the duration of the short circuit.

Although theoretically the current would always occupy the whole of the available period in commutating, practically the current would reach a value closely approximating to its final value in a certain definite time which may be less than the available period. The avail-

able period in a given machine is proportional to the speed, but the natural period was found to be but slightly influenced thereby. The relation which the one period bears to the other, and the actual magnitude of the natural period, determine the efficiency of commutation. By efficiency is meant not merely whether the commutation is sparkless or not, but whether the commutation takes place with the maximum rate of change of current at its lowest possible value. The sparking is determined by the relation of the two periods alone ; if the natural period be less than the available, no sparking will take place, for commutation will be complete before the short-circuit period expires ; when the two periods are just equal the critical sparking conditions exist, and when the available period is less than the natural, the latter is concluded by a spark. The simplest way of varying this relationship is by varying the speed of the machine. Hence there is a certain critical speed below which the machine is sparkless and above which sparking takes place.

If the natural period be less than the available, the value of the maximum rate of change of the current depends upon the duration of the natural period alone, for if the self-induction of the short-circuited coil remain constant, the natural period is dependent upon the magnitude and disposition of the contact resistance of the brush. If these be unsuitable the change of current will be retarded at the commencement of commutation and will be rapidly accelerated at the end. If, however, they be properly chosen, the change of current will be slow at the end of commutation and accelerated during the early stages. The effect of this will be to reduce the maximum value of the rate of change of current over the whole period. Such an acceleration during the early stages of commutation will reduce the duration of the natural period and effect a better distribution of current over the contact surface. Hence although the reduction of the contact surface already described and shown in Fig. 8 increases the apparent current density over the contact surface, the actual current density may be diminished.

When the conditions are such that the natural period cannot be adjusted sufficiently to obtain efficient commutation, an external or commutating E.M.F. must be introduced into the circuit. The primary effect of such an E.M.F. should be to accelerate the change of current during the early part of commutation, and not merely to compensate the self-induction of the coil at the end of the period. Such an accelerating effect may be considered as a compensation of the self-induction, but in whatever light it be regarded, it is essential that it be effective during the early portion of the period. The actual magnitude of the commutating E.M.F. required depends upon the natural period of the coil ; if the E.M.F. be too small or in the wrong direction, sparking will take place at the forward tip of the brush. If, however, it be too large, sparking will take place at the rear tip. Sparking in the former case is due to the available period being too short, and in the latter case is due to the rush of current which takes place instantly the coil is short-circuited, and to the consequent

heating of the first contact. Between these two extreme cases there is a gradual shifting of the commutation backwards from the forward tip of the brush to the rear as the commutating E.M.F. is increased.

If the commutating E.M.F. be provided by means of commutating poles, the presence of the latter considerably increases the self-induction of the coil and the flux due to armature reaction in the commutating zone. The latter must be opposed by an equal flux from the commutating poles before any commutating E.M.F. is generated in the short-circuited coil. The word "oppose" is used advisedly in preference to "neutralise" or "compensate," for reasons given later in the experimental part.

So far nothing has been said with regard to the polarity of the brush, and indeed it is usual not only in theory but in actual experimental work to pay no regard to this point. But it is well known that the contact resistance of the positive brush is different to that of the negative brush, and hence when the conditions of commutation are suitable for a brush of one polarity they are not necessarily suitable for a brush of the opposite polarity. In fact, it is quite possible, as indeed was found in this research, for an alteration of the conditions which improves the commutation under the negative brush to seriously deteriorate the commutation under the positive brush. Thus, for example, the slit cut in the brush, as in Fig. 8, may improve the commutation under the negative brush, but may render the commutation under the positive brush much worse.

These theoretical considerations may be summarised as follows :—

1. In order to neutralise or render non-existent the self-induction E.M.F. of a coil at any instant the relative movement of the field and coil side must take place along the line of action of the resultant field at that instant.
2. Efficient commutation may be effected by a suitable adjustment of the natural period of the coil, and this may be done by properly disposing the contact resistance over the brush surface.
3. When the contact resistance is properly disposed the resistance to the forward segment is relatively high at an early stage of the commutation period.
4. Sparking at the forward tip of the brush is due to the available period being shorter than the natural period.
5. For every machine there is a critical speed at which the available and natural periods are just equal to each other, and below which the machine runs sparklessly.
6. A reduction of the natural period accelerates commutation during the early part of the short-circuit period, and increases the efficiency of commutation by lowering the maximum rate of change of the current, thereby causing a better distribution of current over the contact surface accompanied by a reduction of temperature.

7. The acceleration may be effected by a commutating E.M.F. If the natural period exceed the available period and the commutating E.M.F. be too small sparking takes place at the forward tip of the brush, and if the commutating E.M.F. be gradually increased the commutation is shifted backwards until sparking takes place at the rear tip of the brush.
8. The natural period of the coil when short-circuited by the positive brush is not necessarily the same as when short-circuited by the negative brush.

Section II.—The Brush-holder.

The theoretical conclusions enumerated above were found to be experimentally true, but before dealing with them from the experimental side certain serious difficulties which were encountered in connection with the brush-holder will be described.

In the early stages of the research it was found that the commutation was exceedingly irregular; not only was it different for different segments, but it changed from time to time. On reference to other researches in which commutation oscillations were shown it was noticed that these showed similar irregularities. In many published results these irregularities were stated to be due to variation of the contact resistance between the brush and the commutator, and were regarded as a natural defect in the particular machine employed, and impossible of prevention. It was, however, of the greatest importance to find the cause of these irregularities, and if possible to overcome them, as while they were present accuracy was quite impossible, and none of the phenomena recorded in this paper could be observed with precision and related to their proper causes. It was thought that these irregularities were mainly due to mechanical defects of the brush-holder, and as the work proceeded this view was fully confirmed.

The commutator was turned up and the mica scraped out from between the segments to a depth of about 1 mm. Several types of brush-holder were tried, including the finger and reaction types, but with all these the contact surface was by no means constant. This was found to be due to a variable coefficient of friction between the carbon and the commutator surface, and to slight differences in the commutator surface. The incapability of the brush to adjust itself automatically to such varying conditions caused the commutation to be very uncertain in its nature. The author had the opportunity of examining some of the most modern brush-holders in actual use, and found that in all these the same difficulties existed, that the contact surface was not certain, and that the contact pressure was not uniformly distributed. A very common evidence of this is that the surface, when newly rubbed up with emery paper and allowed to polish by running the machine, polishes up first at the rear tip owing to the tipping effect of the friction.

A few examples of the commutation oscillations obtained are given in Fig. 9, and a comparison of these records with those given later will show the unreliable nature of the commutation effected by the ordinary type of brush-holder. A new brush-holder was designed and constructed entirely free from these objections, and was used in all the experiments described in this paper.

The photographs shown in Figs. 10 and 11 illustrate the brush-holder. Fig. 10 shows the holder put together for use, and Fig. 11 shows the various parts.

The holder consists of a carrier A mounted on the brush-bar and clamped thereon by the screw B. A double plate C is mounted and capable of sliding on the carrier A, and is guided in its motion by a stud

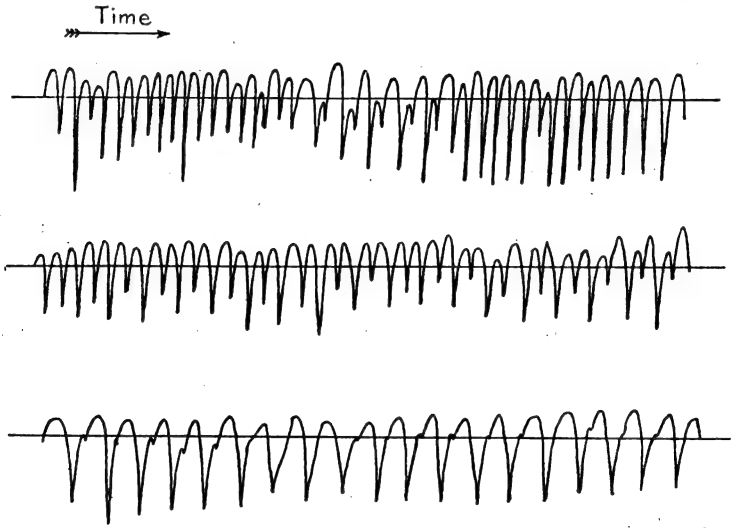


FIG. 9.—Magnetic Oscillations in Pole-shoe with Ordinary Type of Brush-holder.

working in the slot D, and can be clamped in any position by the screw E. Two metal frames, F_1 and F_2, are held against this plate by the springs G_1 and G_2, respectively, in the positions shown. Their lower ends are formed into half-bearings, which press on to the axis H, upon which the carbon is mounted. The carbon is free to rotate upon the axis H, and is prevented from moving with the commutator by the tangential force exerted by one of the frames F; one frame corresponds to each direction of rotation, and is inoperative in this respect when the rotation is reversed. Either end of the brush axis is free to lift independently of the other end. Hence the brush is free to adjust its position to any change in the commutator surface radially, circumferentially, and laterally. When this brush-holder was in use the surface of the carbon was always uniform, and the commutation remained always the same, even if the brush were removed and then replaced.

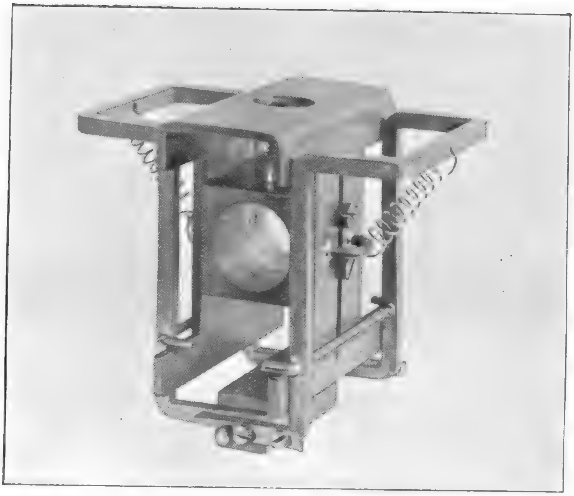


FIG. 10.—Brush-holder.

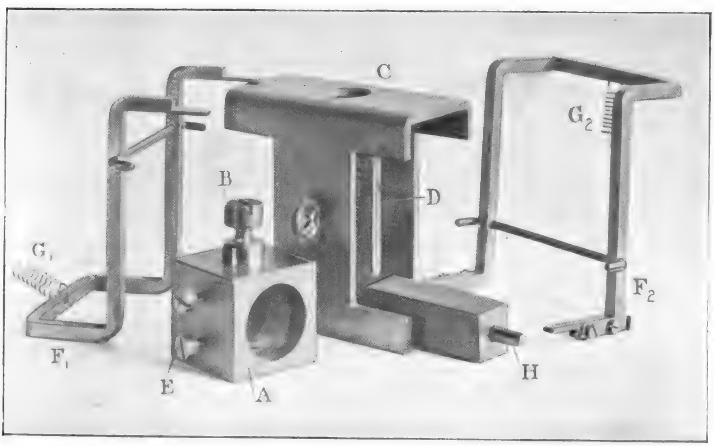


FIG. 11.—Brush-holder.

The brush-holder was of great service not only in this research, but in other researches carried out at Karlsruhe, where similar difficulties had been experienced.

Section III.—Introduction to Experimental Results.

The commutation phenomena already theoretically considered were experimentally studied by means of the magnetic oscillations recorded in coil 5 P on the pole-shoe.

The oscillations recorded were due both to the movement of the teeth in the main magnetic field and to the commutation of the armature current; but, as will be seen from Fig. 12, the two kinds of oscillations were easily distinguished from each other. In this figure A shows the tooth oscillations alone as recorded on open circuit, and B the oscillations recorded on full load. C and D are records obtained by running the machine as a generator with full-load resistance in circuit, but with only one commutator brush down, the circuit being completed through a slip-ring connected to a point in the armature. In record C the the negative commutator brush was employed, and in A the positive brush. In these two latter records, when the tapping-point was in the neighbourhood of the commutator brush, only the tooth oscillation was recorded, and as the tapping-point rotated the commutation oscillation appeared until when the point was opposite the commutator brush the oscillation reached its maximum value. Thus C shows the magnitude of the oscillation due to the negative brush, and D that due to the positive brush.

The magnitude of the positive brush oscillation was very much smaller than that due to the negative brush. This difference was not due to any lack of symmetry of the magnetic system, for both brushes behaved in a similar manner when changed in polarity, but entirely to a difference in the natural period of the short-circuited coil when under the positive and when under the negative brush.

Since the magnitude of the positive brush oscillation was less than that of the negative, the natural period of the former was less than that of the latter, and since it may be assumed that the self-induction in the two cases is the same, it follows that the contact resistance of the brush when positive was higher than when negative. This result agrees with those obtained by Arnold and others in their measurements of the contact resistance of this type of carbon.

The commutation oscillation consists of a single peak; the magnitude of the peak is proportional to the maximum rate of change of the current in the short-circuited coil, and its magnitude and position in relation to the contact maker indicate the nature of commutation taking place. When the peak is small and occurs early, the commutation is efficient; but when the peak is large and occurs late in the period, the commutation is completed by a rush of current and sparking is liable to take place.

The resultant oscillation in a given machine may have eight

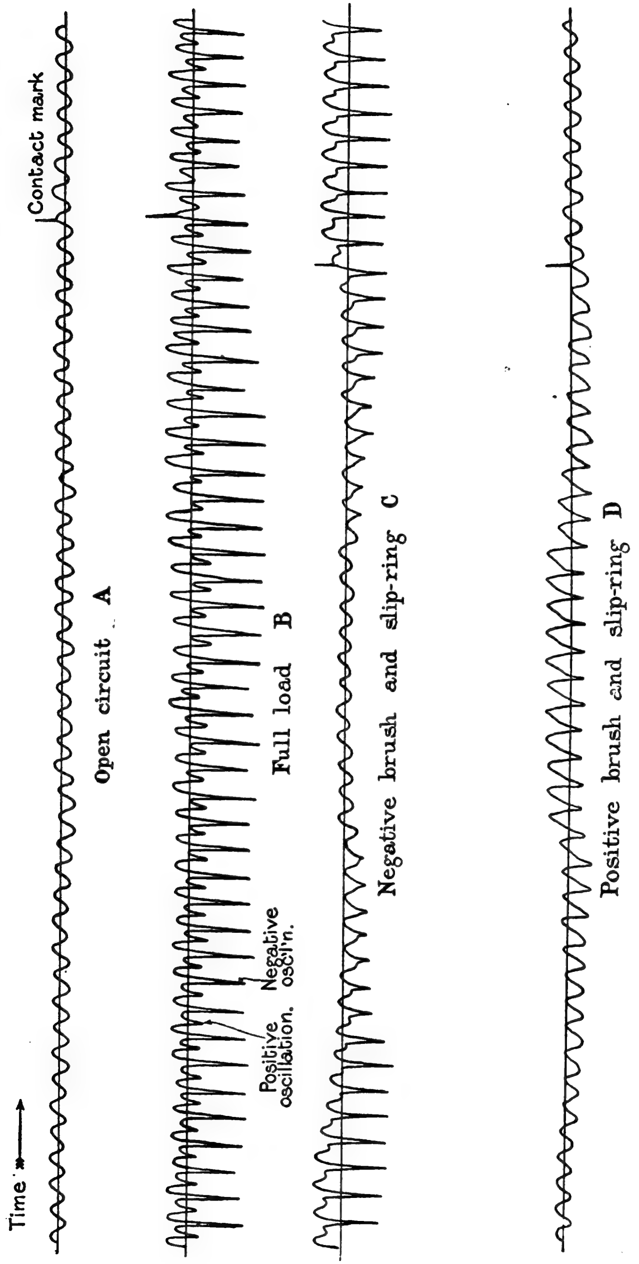


FIG. 12.—Composition of Magnetic Oscillations in Pole-shoe.

different shapes. The shape is determined by three factors: *i.e.*, direction of rotation, direction of current, and direction of field. Fig. 13 shows the various shapes of oscillations obtained, and the circles to the right of the figure show the relations of the three factors referred to. The curved arrow indicates the direction of rotation, the horizontal arrow that of the current, and the vertical arrow that of the field. The tooth oscillation changes in direction when the field is reversed, and where the direction of rotation is reversed, hence a reversal of both field and rotation has no effect upon it.

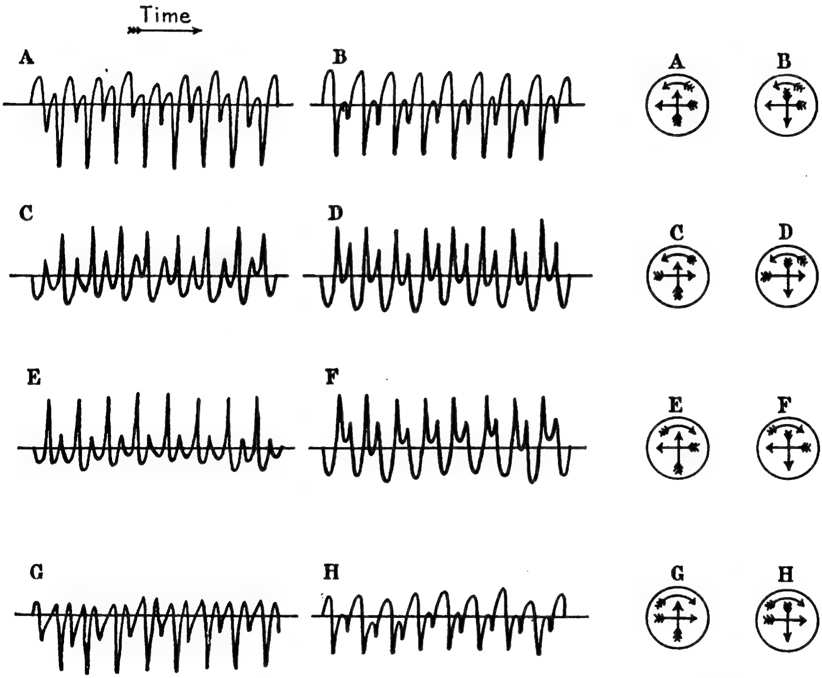


FIG. 13.—Direction of Armature Current, Field and Rotation varied.

The commutation oscillation changes in direction when the direction of current changes, and the positive and negative oscillations interchange in position, the other factors remaining the same. A reversal of rotation has two effects: firstly, reversal of direction; and secondly, a displacement as regards time. This latter is due to the peak occurring at the end of the short-circuit period; when the rotation is reversed, the peak therefore shifts to the left in the record about one-half a period in relation to the tooth oscillation. A reversal of both current and rotation causes no change in the direction of the oscillation, only a change in the position.

If the commutation oscillation peak occurred exactly at the middle of the period, record G would approximately correspond to A, record H to B, record E to C, and record F to D, and there would only be four varieties of resultant oscillation.

The movement of the peaks to the left can be very clearly seen by comparing the records as above.

Still another variation can be given to the shape of the resultant oscillation by shifting the brushes through a fraction of a period, and thus displacing the phase of the commutation oscillation in relation to the tooth oscillation.

The actual magnitude of the negative peaks when produced by the normally positive brush is not exactly the same as when produced by the normally negative brush, and *vice versâ*. This is partly on account of their differing relation to the tooth oscillation, and partly on account of the fact that a brush normally positive required to run a very long time before it became a normal negative one. The change did take place if sufficient time was given (usually several days continuous running), but it was not thought necessary for the purpose of these

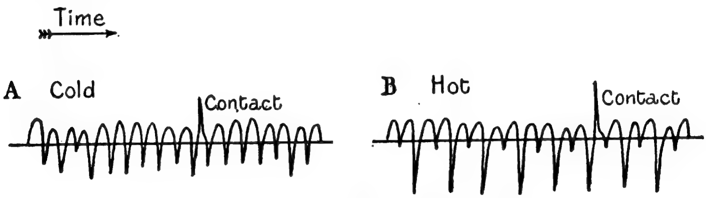


FIG. 14.—Commutation Cold and Hot.

records to spend the time necessary to effect a complete change. The reason for this curious phenomenon will be explained in Section IX.

SECTION IV.—THE INFLUENCE OF CONTACT RESISTANCE ON COMMUTATION.

In the last section it was shown that the difference of resistance of the positive and negative brushes had a very marked influence on the commutation taking place. This influence was also noted in the commutation obtained when the commutator was respectively cold and hot. Fig. 14 shows the records obtained. A was recorded when the commutator was cold after standing over the week-end; temperature of room 15° C. B was recorded after the machine had been running several hours and the commutator had attained the temperature of 29° C. The negative oscillation increased considerably with rise of temperature, while the positive oscillation diminished slightly. This was caused by a decrease in the contact resistance of the negative brush, while that of the positive brush varied but little. Such sensitiveness of the negative brush resistance and lack of sensitiveness of the positive to change of temperature is confirmed by Arnold's measurements of the contact resistance of the carbon used in this research.

The influence of the contact resistance on commutation is further demonstrated by Fig. 15. A was obtained under normal full load running conditions, and B was obtained under the same conditions, but when a little petroleum had been rubbed on the commutator. The petroleum increased the contact resistance and thereby reduced the natural period of the short-circuited coil with the resulting diminution of the oscillation and the maximum rate of change of the current.

It should be mentioned that the petroleum is very difficult to remove from the commutator, and the least trace is sufficient to

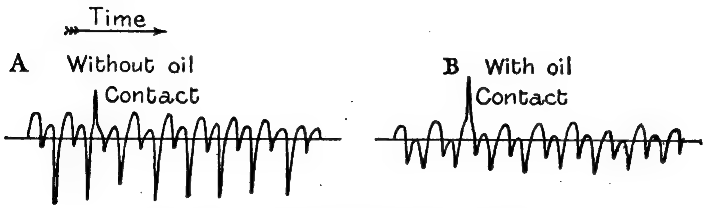


FIG. 15.—Effect of Oil on Commutator.

influence commutation. This last experiment was therefore only done when all the other experiments had been completed.

It might be thought that an increase in the contact resistance would considerably increase the brush losses, but it must be remembered that with the improved commutation the current is more uniformly distributed over the contact surface, and further, the small magnitude of the oscillation will cause the iron losses to be reduced.

SECTION V.—THE DISPOSITION OF THE CONTACT RESISTANCE.

It was pointed out in the theoretical section that commutation could sometimes be improved by a proper disposition of the contact resistance over the brush surface. This was effected in the present research by means of the brush shown in Fig. 8. A series of records was taken of the oscillations occurring in coil 5 P on the pole-shoe with various widths of contact surface at the forward tip of the brush. These records are shown in Fig. 16. The shape of brush corresponding to each record is shown in the figure. Only the negative brush was varied, as the commutation under the positive brush was already very satisfactory. The negative oscillation was gradually reduced in magnitude as the width of the forward portion of the brush surface was reduced, until the width of the latter was a minimum consistent with mechanical strength.

In this shape of brush the contact surface of the brush is equally divided between the two segments, when about one-quarter of the short-circuit period has expired, and just before one-half the period the contact resistance over the forward segment is confined to the narrow strip at the forward tip of the brush.

The reduction of magnitude of the oscillation is, as pointed out in the theoretical part, due to earlier commutation. This can be very clearly seen by means of the contact mark on the records. The peak of the negative oscillation gradually moves to the left, and since time is towards the right and the contact mark indicates a fixed position of the armature, the peak occurs earlier as the contact surface is reduced. The positive oscillation peak remains in a fixed position, and hence the two peaks gradually approach one another.

With a full surface the negative brush had a tendency to spark on full load, but when the forward surface was reduced to 2½ mm. all sparking disappeared, and with a 2-mm. surface the machine could be run on a 75 per cent. overload without any trace of sparking. Thus the overload capacity of a machine may be greatly increased by a suitable disposition of the contact surface.

The actual dimensions of the two portions of the contact surface suitable for any given type of machine depend upon the self-induction of the short-circuited coil and the specific contact resistance of the

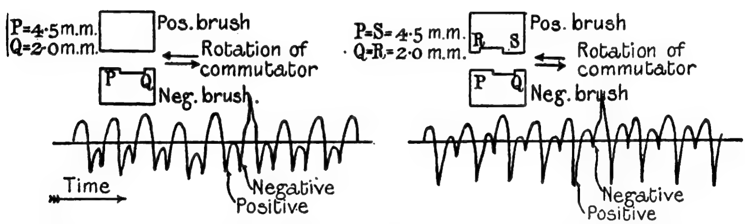


FIG. 17.—Effect of divided Surface on Commutation under the Positive Brush.

carbon employed, but they can always be determined by means of a search coil on the pole-shoe and the oscillograph as in this research.

The same experiment was tried with the positive brush, but with very different results. As will be seen from the above figure, the positive oscillation was very small even with the full surface, and hence any alteration in the brush surface could hardly improve matters, as the commutation was already so very satisfactory. The brush was cut away in exactly the same way as in Fig. 16; but, as will be seen from Fig. 17, the oscillations immediately increased to about the same magnitude as those due to the negative with the full surface brush.

A superficial consideration of the divided brush might lead one to suppose that the commutation would take place in two successive rushes, one related to each portion of the brush surface, and that but very little change of current would take place during the period in which the contact resistance to each segment remained constant. If such were the case the natural period of commutation would be increased and the efficiency of the brush would be seriously impaired. This, however, is not the case, as the two rushes of current are prevented by the retarding action of the self-inductance of the short-circuited coil.

In the case of a full surface brush, when a rush of current takes place at the end of the short-circuit period most of the current is carried by the forward portion of the surface until the high resistance of the latter accelerates the commutation. Thus the effective surface of the brush for current carrying is much smaller than the actual surface. In the divided brush all the surface is effective. Thus the effective surface in the two brushes may not be very different, and the temperature rise as a consequence may not be increased, although the actual surface of the brush is reduced.

Section VI.—The Influence of Speed on Commutation.

It has already been pointed out that the natural period of commutation is but slightly influenced by the speed. The reason for this may be seen from the following considerations :—

At a given time after the commencement of short circuit the contact resistance to the forward segment is increased, while that to the rear segment is reduced by an increase in speed. Such a change in the resistance will diminish the natural period of the coil, but not in proportion to the speed, while the available period is diminished in proportion to the speed, and the ratio of the available to the natural therefore diminishes as the speed increases. At a certain critical speed therefore the ratio is unity, and this is the critical sparking speed.

Fig. 18 shows a series of records of the oscillations occurring in coil 5 P on the pole-shoe obtained by varying the speed of the machine. The negative peak moves to the left as the speed is diminished, and hence occurs earlier. At a speed of 640 revs. per minute the peak occurs just before the contact mark, which latter was adjusted to the commencement of the short circuit; hence at this speed commutation was completed by a current rush, and when the speed exceeded this value the natural period exceeded the available and sparking took place. In order to make quite sure that the improvement of the commutation at the lower speeds was due to a change in the available period of the coil, the machine was run with the poles not excited, and the armature current supplied from an external source. Fig. 19 gives the records obtained which exhibit the same characteristics as those in Fig. 18.

This critical no-sparking speed of 640 revs. per minute was quite definite even to a few revolutions, and could readily be determined by gradually increasing the speed until sparks appeared.

Although the available period increased as the speed was diminished, the magnitude of the commutation peaks was but slightly reduced, and in relation to the contact maker moved to the left, or if the position of the peak be considered as fixed, the contact maker moved to the right in the direction of time—*i.e.*, the extension of the available period occurred at the end of commutation, or in other words, the natural period remained nearly constant, and maintained the same relation to the commencement of commutation.

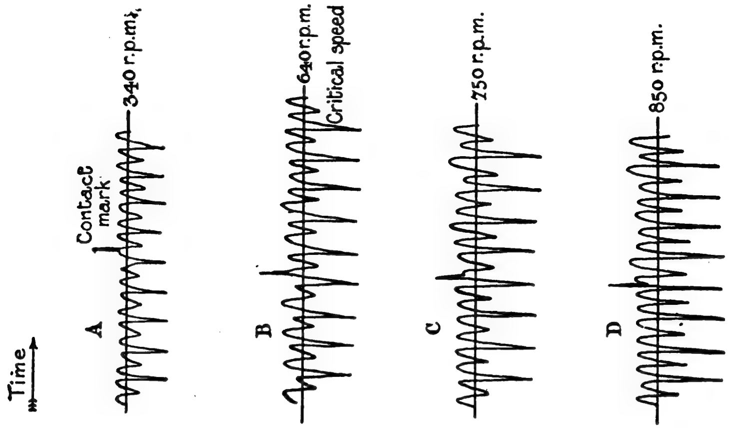


FIG. 19. Effect of Speed on Commutation—no Field.

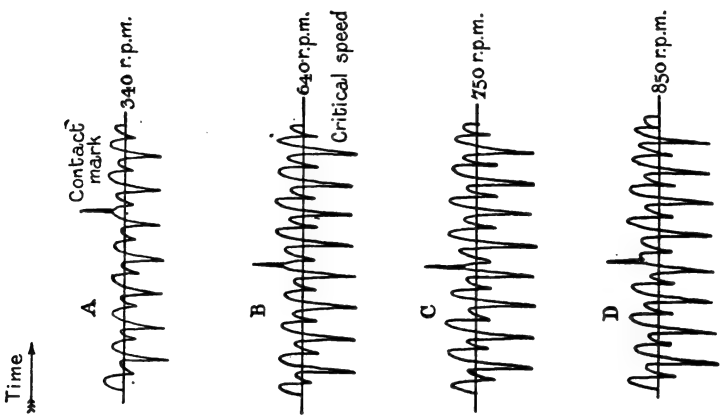


FIG. 18.—Effect of Speed on Commutation—Normal Field.

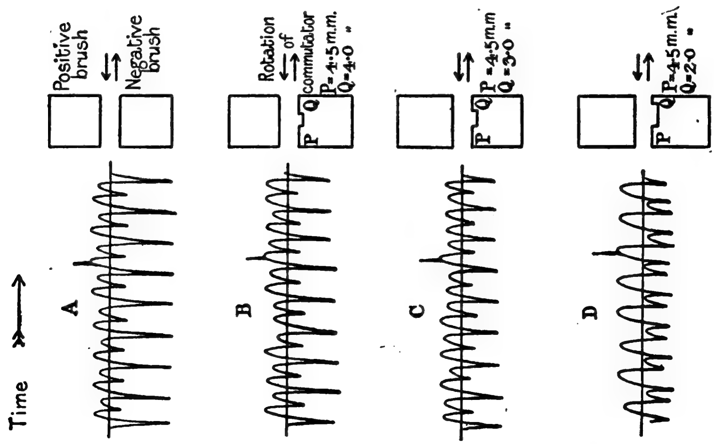


FIG. 16.—Negative Brush divided.

SECTION VII.—INFLUENCE OF COMMUTATING E.M.F. ON COMMUTATION.

It has already been pointed out that instead of altering either the natural or available period of commutation, an external factor may be introduced and the commutation may be accelerated by means of a commutating E.M.F. Such an E.M.F. must necessarily be in the same direction as the main current in the short-circuited coil after commutation. The E.M.F. may be induced in the short-circuited coil by its movement either in a portion of the main magnetic field or in the field due to commutating poles.

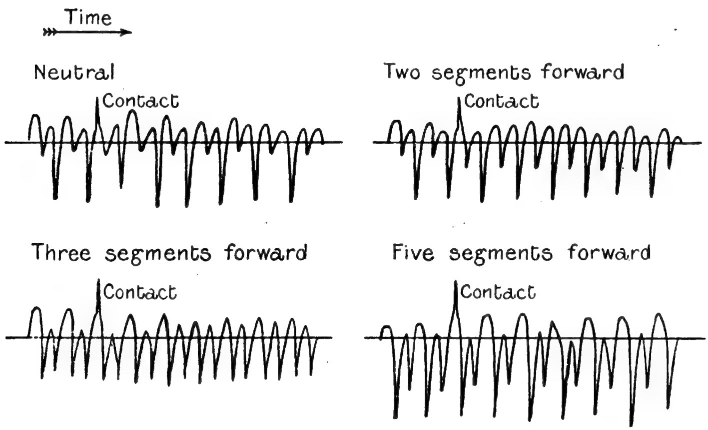


FIG. 20.—Position of Brushes varied.

If the induced E.M.F. be constant or follow a known law the way in which the current varies may be expressed by the differential equation—

$$L\frac{di}{dt} = r_2 i_2 - r_1 i_1 + e_c,$$

where e_c = commutating E.M.F.

The E.M.F. should be sufficiently large during the early part of the short-circuit period to accelerate the commutation at the commencement. The effect of the acceleration in reducing the natural period and the maximum rate of change may be readily seen from Figs. 20 and 21. The various records in Fig. 20 were obtained by shifting the brushes forward by steps of one or more segments. The magnitude of the negative oscillation gradually diminishes and the peak moves to the left—that is, occurs earlier—as the brush lead is increased. At the same time the positive oscillation is considerably increased.

When the lead is such that there is a relatively large E.M.F. induced in the short-circuited coil at the commencement of short circuit a rush

of current takes place at the first contact with the approaching segment, and the contact may be so heated that the continuity of contact is broken and a spark occurs at the rear tip. If the E.M.F. be so large at the end of the commutation period as not merely to reduce the current flowing through the forward segment to zero, but to reverse its direction, a spark occurs at the forward tip.

The common conception of an induced short-circuit current in the coil can only hold in the latter case above described; unless the current in one of the segments be actually reversed no current can flow across

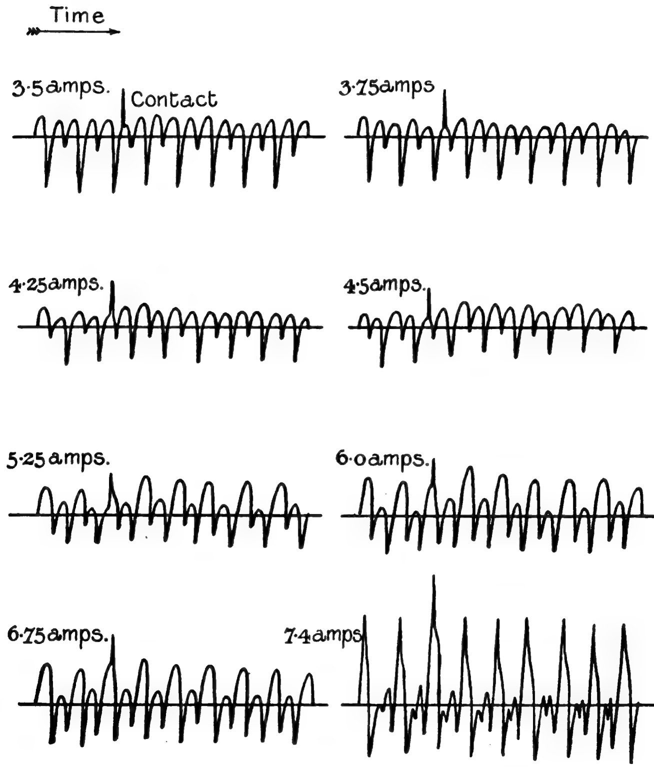


FIG. 21.—Commutating Pole Current varied.

the brush surface, for the effect of the commutating E.M.F. when of normal magnitude is simply to increase the current in the rear segment and diminish it in the forward segment.

In the records given in Fig. 21 the commutating E.M.F. was induced by means of commutating poles. The width of each pole was $2\frac{3}{4}$ times the armature tooth-pitch. The commutating poles were separately excited and the field was varied from a minimum for no sparking to a maximum for no sparking. Such variation of the field

produced effects similar to those obtained by shifting the brushes above described. The short-circuit current at the end of commutation is clearly shown by the large peak above the zero line.

The presence of the commutating poles increases the self-induction of the coil, and therefore the natural period is increased; hence if the natural period be correct without commutating poles it may be too long when commutating poles are fitted. In such a case a commutating E.M.F. is required to compensate the increased natural period.

The presence of the commutating pole, however, not only increases the self-induction of the short-circuited coil, but also increases the armature reaction flux in the commutating zone. This latter must be opposed by an equal flux from the commutating pole before any flux is available to generate the required commutating E.M.F. The two fluxes oppose but do not cancel one another in the commutating pole air-gap. The effect of such opposition is to spread out the fluxes in much the same way as the flux of two permanent magnets with similar poles presented to each other.

The surface of the commutating poles remains constant, but that of the armature varies as the teeth move past the pole-face. Such variation gives rise to a corresponding change in the magnitude of the armature flux opposed by the commutating pole flux; thus when the commutating pole flux is equal to the minimum value of the armature flux, the periodic increase of the latter enters the commutating pole-face and induces an E.M.F. in a coil wound round the commutating pole-shoe. As the pole flux is increased this magnetic oscillation is diminished, and the excess of the commutating pole flux over the armature reaction flux enters the armature and generates a commutating E.M.F. This latter flux is also subject to an oscillation owing to the movement of the teeth, which induces an E.M.F. in the search coil above referred to. The armature reaction oscillation, however, although diminished in magnitude continues to exist, for whatever be the magnitude of the commutating pole flux the two opposing fluxes remain independent of each other. The two oscillations, being produced by opposing fluxes, are approximately 180° out of phase with each other.

Thus the resultant oscillation exhibited by coil 9 P on the commutating pole-shoe forms a convenient method of studying the nature of the field in the commutating pole air-gap. In Fig. 22 are given the oscillations recorded corresponding to various commutating pole-currents between the two extreme sparking limits.

On record A the main oscillation is due to the armature reaction flux, the slight indent in the oscillation indicates that the commutating pole flux is greater than the armature flux. The indent grows and in record B is about one-half the magnitude of the main oscillation, while in record C the original indent is larger than the original main oscillation. This may be seen by the position of the contact maker relative to the two oscillations.

As the commutating pole current is increased, the oscillation of the

commutating pole flux rapidly grows until in record F the original indent becomes the main oscillation, and the original oscillation almost an indent.

These records were taken at the same time as those given in Fig. 21, and hence each record given in Fig. 22 shows the condition of the field in the commutating pole air-gap, while the corresponding record in Fig. 21 shows the nature of the commutation obtained. A comparison of the two sets of records shows that for no sparking a slight commutation E.M.F. was required, but that there was a large range before the maximum permissible E.M.F. was reached.

It might be thought that the oscillations above described were due to some interference on the part of the main poles or the other com-

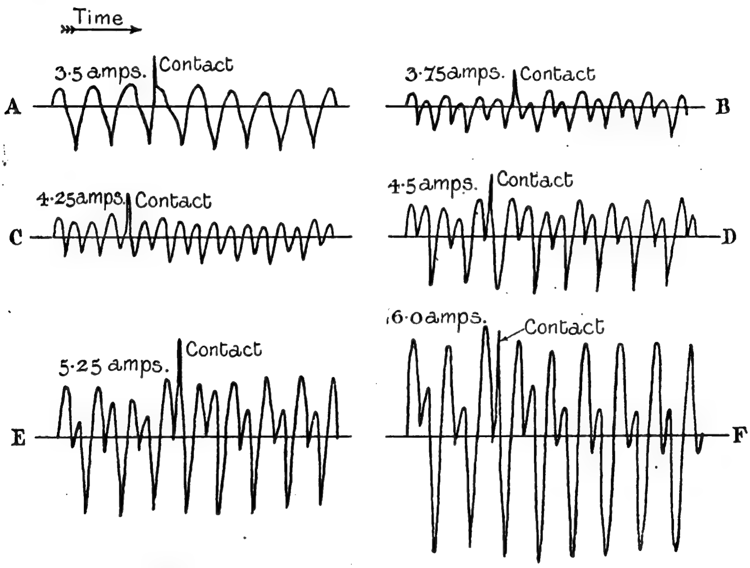


FIG. 22.—Magnetic Oscillations in Commutating Pole-shoe—Commutating Pole Current varied.

mutating pole. That the oscillations were not due to interference on the part of the other commutating pole was shown by the fact that a similar series of results was obtained when the other commutating pole was removed. In this case the minimum value of the commutating pole current for no sparking was but slightly greater than when two poles were fitted, but the maximum value was double.

This clearly shows that the commutating pole flux fulfils two functions: first, to oppose the armature reaction flux in the commutating zone; and secondly, to provide a commutating E.M.F. The first acts as pole against pole, the armature flux is not cancelled but only opposed. Each commutating pole deals with the pole-strength of the armature on its own side, and is not influenced by the presence or absence

of the other pole. The commutating E.M.F., however, must be of approximately the same magnitude whether there be two poles or only one, and hence if the E.M.F. be generated in one side only of the short-circuited coil the flux generating it must be doubled.

Hence, when the commutating flux is small compared to the opposing flux, the ampere-turns required per pole are only slightly greater when only one pole is used than when two are in use, while when the commutating flux is large compared with the opposing flux, the ampere-turns required are practically double. Hence the use of one pole may affect a considerable saving in copper, and the range of commutation is greatly increased.

Section VIII.—The Width of the Commutating Pole.

Fig. 23 shows the E.M.F. curve recorded in coil 2 A wrapped round the middle of an armature tooth. A is the curve recorded when the

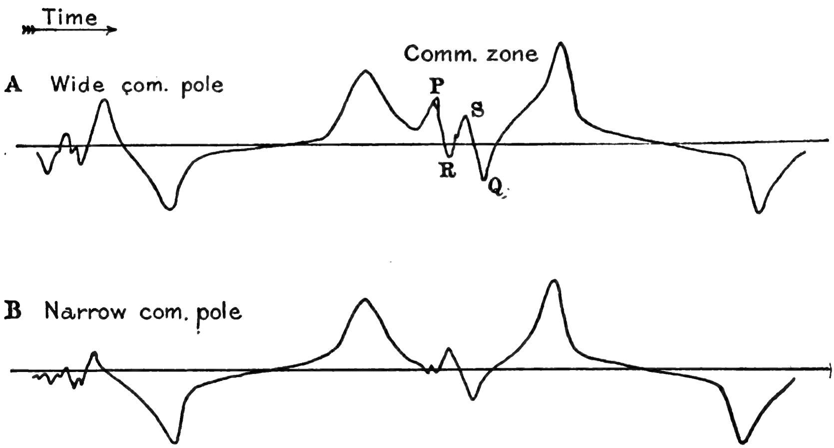


Fig. 23.—Magnetic Oscillations in Middle of Tooth.

width of the commutating pole is $2\frac{3}{4}$ times the armature tooth-pitch. The two extreme peaks, P and Q, in the commutating zone are due to the flashing of the flux across the slot, one as the coil enters under the commutating pole, and the other as it leaves. Between these two peaks two others, R and S, occur due to the commutation pulsation. The one to the left occurs in the tooth when to the rear of the slot being commutated, and to the other when it is in front.

The four peaks are alternately above and below the zero line, and are of the same order of magnitude. The position of the inner peaks is fixed by the commutation conditions, but the distance apart of the outer peaks may be varied by varying the width of the commutating poles. If the width were so adjusted that the two outer peaks were

superposed on the inner ones the four peaks might be made practically to disappear. In order to ascertain if this were possible narrow commutating poles were fitted, equal to $1\frac{3}{4}$ times the tooth-pitch, and the position of the brushes slightly adjusted so that the two left-hand peaks were superposed. The magnitude of the commutating pole current was also slightly reduced, and record B in the same figure was obtained.

If the oscillation in the tooth be neutralised the losses will be reduced and the efficiency of the machine increased. In the experiment only one commutation oscillation was neutralised, but if the width of the pole had been further reduced the other oscillation could have been neutralised in the same manner.

The velocity of the coil side relative to the flux is greater during the flash than when the slot is under the pole-face, hence the flux required would be less, and the ampere-turns could be reduced.

Section IX.—The Cause of the Difference in Behaviour of the Positive and the Negative Brushes.

In many theoretical discussions on commutation the influence of one brush upon the other is considered, but no physical difference which may exist between the two brushes is taken account of. Many also who have experimentally investigated the subject have paid no regard to the polarity of the brush. Those, however, who have made measurements of the physical properties of each brush individually, such as the measurement of resistance and friction, have noted a very marked difference between them. No law appears to hold which could be applied to all conditions of running, and to all brush materials, but the general observed result is that the negative brush is much more sensitive than the positive to change in temperature, current density, etc.

Two observations in this direction were repeatedly made in this research, viz., that the warm brush vibrated very considerably when negative, but the same brush ran quite smoothly when positive, and that the surface of the negative brush was very much more highly polished than that of the positive. The vibration was entirely prevented by laying about six thicknesses of copper foil, each 0·035 mm. thick, on the forward tip, and a strip of copper on the rear tip, the metal being held in close contact with the brush by means of a copper clip; the metal was insulated from the carbon by very thin strips of mica. Both brushes were fitted in this way for the sake of uniformity.

The reason for this was thought to be as follows: The heat generated at the brush contact surface caused that surface to expand slightly, and the forward tip, being shielded from all draughts by virtue of its position, was subject to the greatest expansion, and actually lifted from off the commutator. The lifting was not continuous, but periodic; as a cold segment came under the tip, the latter came into contact with

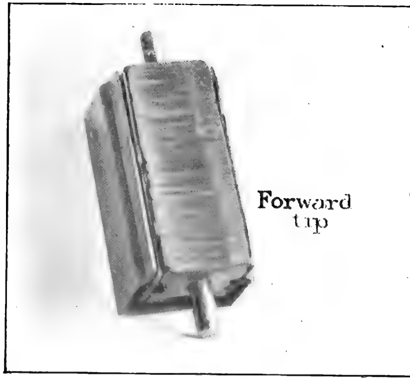


FIG. 24.

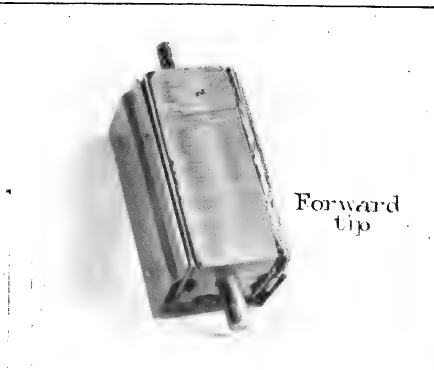


FIG. 25.

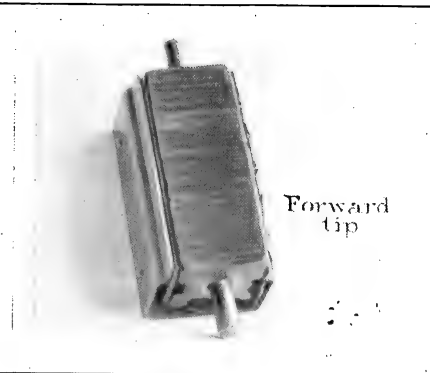


FIG. 26.

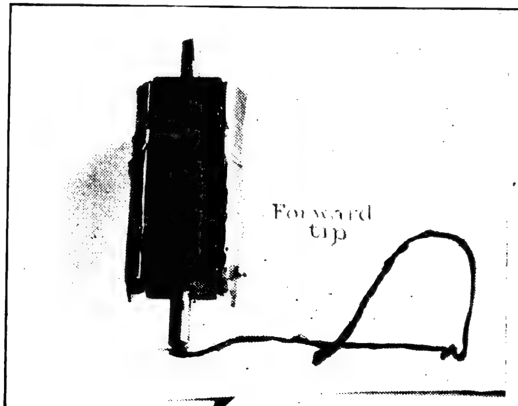


FIG. 28.

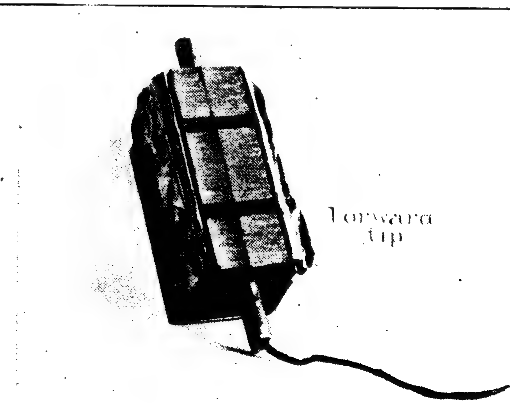


FIG. 29.

the commutator, but when the segment was heated by the current the tip was lifted off again. Thus a high-frequency vibration was set up which was communicated to the whole brush. The heat generated at the tip was not readily conducted away by the carbon, but the superior conductivity of the copper strips carried the heat away, and the large surface of the clip served to radiate it. The polished surface of the negative brush was due to its high temperature.

This theory was fully substantiated by the following experiments:—

1. A brush polished up and in use for some time without the metal cooler was observed to have a band of brown nearly half the width of the brush on the forward part of the contact surface ; slight sparking also took place. The metal cooler was then fitted, and after about 2 hours' running, the band of brown was found to be entirely rubbed away, while a new band appeared down the middle of the brush. No sparks were visible at the tip, but at the side of the brush about the middle an occasional spark appeared. The brush vibrated very considerably without the cooler, but with the cooler it ran quite smoothly, and the running was observed to improve as time went on.
2. With a very weak commutating pole-field the current commutated very irregularly even with the cooler used in experiment 1, and a brown band $3\frac{1}{2}$ mm. wide formed on the forward tip of the contact surface. The surface is shown in the photograph in Fig. 24. When the field was strengthened regular commutation was obtained, and the brown band was rubbed away as shown in Fig. 25.
3. The commutating field was weakened as in experiment 2 and the brown band again obtained. The thickness of metal on the forward tip was then trebled, and regular commutation was obtained with the same commutating field, and the brown band was rubbed away as shown in Fig. 26.

No sparking took place in either case when regular commutation was obtained.

From experiment 1 it is evident that with the cooler the brush was running on the two tips and the centre was not in proper contact with the commutator, and it may be concluded that without the cooler the forward tip was in bad contact with the commutator. It thus appeared that the surface of the brush expanded, but the cooler cooled the tips, thereby causing the curvature of the surface to be greater and the tips to come into contact with the commutator.

Experiment 2 shows the same effect ; when the commutating field was weak the high inductance of the armature, owing to the presence of the commutating poles, caused the current to commutate very slowly, and consequently the forward portion of the brush surface carried a heavy current. This made the tip hotter than when there were no

commutating poles, and hence the expansion took place, the bad contact at the tip caused the brown appearance and made the commutation irregular. When, however, the field was increased, the current density at the brush tip was reduced and the tip ran cooler.

In experiment 3, when the tip was cooled by the extra metal, it was also kept in contact with the commutator and the brown band was polished off.

The observation that the negative brush was more highly polished than the positive may be considered in conjunction with another observation, *i.e.*, that the brushes after being freshly ground up would not take a good polish until current flowed through them. This was due to the warming effect of the current. Hence the degree of polish depends upon the temperature of the brush surface, and since the polish on the negative brush was better than that on the positive, it follows that the negative brush is hotter than the positive. The highly polished surface will make better contact, and hence the contact resistance of such a surface will be lower. Thus it is that the resistance of the negative brush is lower than that of the positive and the natural period is greater.

When the polarity of the brushes was reversed, the negative brush required a long time before the polished surface was worn away, and the positive brush required some time to acquire the polish of the negative, although the latter time was much shorter than the former. The gradual change in the oscillations due to the two brushes when the polarity was reversed could be easily watched in the revolving mirror of the oscillograph. Thus the phenomenon noted at the end of Section III. is explained.

The difference in temperature between the two brushes is accentuated by the manner of commutation, but if the difference in temperature is the cause of the difference in commutation, the former phenomenon must be due to a cause entirely outside the phenomena of commutation.

In order to ascertain this the following experiment was carried out: A carbon brush of the same material and shape as was used in the other experiments was placed on a thick piece of brass, and bedded down on to it by several thicknesses of copper foil. A slit was cut in the brass and foil, and a thermocouple was introduced into it so as to touch the carbon surface. The couple was composed of copper and constantan, separated from each other up to the joint by a thin strip of mica, and laid between two sheets of asbestos. The other element in the thermocouple was placed in a vessel of water in which a mercury thermometer was placed. The whole apparatus was carefully screened from draughts.

Current was passed through the apparatus from carbon to copper, and also from copper to carbon. In the former case the carbon corresponded to a negative dynamo brush, and in the latter to a positive dynamo brush.

Readings were taken for a series of currents in both directions.

For each polarity the temperature was read when the current was reversed after reading for the opposite polarity, and also after being switched on when the apparatus was cold. The apparatus required three or four hours to obtain a steady temperature. Thus for a positive polarity the reading was taken after the brush had cooled from being negative, and also after heating up direct from cold. The readings

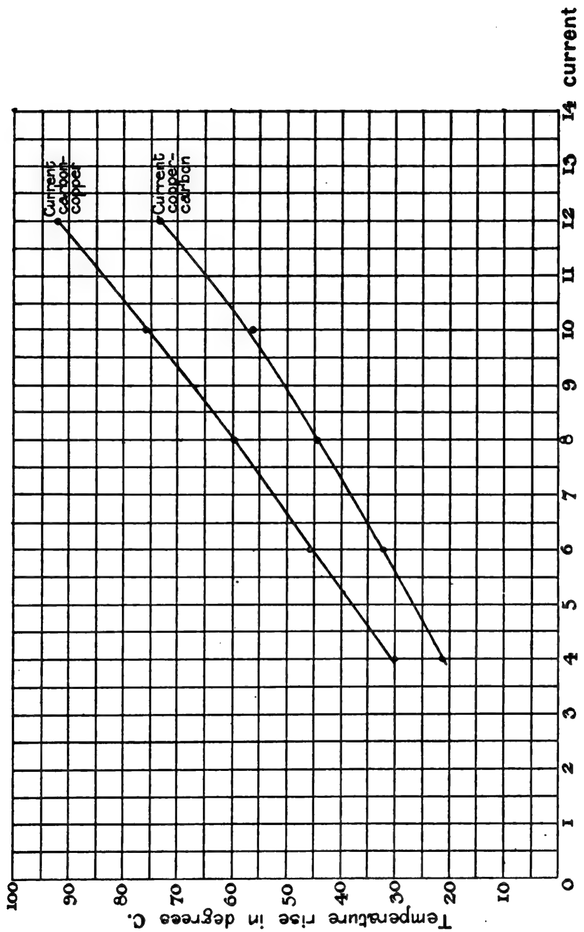


FIG. 27.

obtained were within 1 or 2 per cent. of each other and the mean was taken. The readings obtained are shown in the curves Fig. 27, in which the temperature rise is plotted against the current flowing. From these curves it will be seen that the difference in temperature is increased as the temperature rises.

The temperature of the actual commutator brush was also measured

when the machine was running. The brush normally negative was fitted with a thermocouple on the forward tip as near to the contact surface as possible. The couple was in contact with the carbon and covered by a thick layer of asbestos, the whole being clipped on by a copper clip. The rise of temperature obtained when the brush was negative was 19·4° C.; the polarity was then reversed, and the temperature gradually dropped until a rise of 15·2° C. was obtained. The temperatures measured are, of course, less than the actual temperatures of the contact surface owing to the low heat conductivity of the carbon brush. The divided brush was afterwards put into position, and the temperature rise of the forward tip measured in the same way and found to be 14·8° C., which is slightly less than that obtained when the full surface positive brush was in position. This shows the possibility of reducing the temperature by improving the current distribution, although in doing so the actual area of the brush may be reduced.

The explanation of this phenomenon lies somewhat outside the domain of electrical engineering, and the author had no opportunities of extending the experiments in this direction, but it is evident that this physical fact is the basis for the whole of the phenomena associated with the polarity of the brush.

Evidence of the expansion of the brush contact surface was also observed by Dr. Fraenckel and Mr. Lane* in connection with some experiments on an alternating-current commutating motor, in which he also adopted the author's brush-holder and cooling device. The photograph in Fig. 28 shows the brush surface with a small current density, and Fig. 29 with a much higher value. In the first case the tips were maintained cool, but the inner portion of the surface expanded and made bad contact with the commutator, with the result that the carbon was burned and a brown band formed. In the second case the cooling was not sufficient, and the tip expanded and made bad contact with the commutator. In these experiments, as in those of the author, the cooler formed an excellent anti-sparking device.

It has already been pointed out that the temperature of the brush-tip is probably not quite constant, but is cooled on first coming into contact with a cool segment and then gradually heated up as the segment passes under the brush. This would cause a periodic variation of contact resistance, and if the heating of the tip were sufficient, the tip would actually break connection with the segment and strike an arc through which the current would flow. The potential difference between the brush and the segment would perhaps not be high enough to maintain an arc of any appreciable length, but the potential difference required to maintain an arc between two plates a very short distance apart is only a few volts, and since in the case of the brush the gap would be of a very small order of magnitude the possibility of such an arc is quite feasible. The burning action of the arc produces the brown band on the brush surface and a deposit of the same width on the commutator segment. If the band and deposit had been due to

* *Electrician*, vol. 65, pp. 231, 269, 325, and 364, 1910.

sparks at break, the band would have been confined to a very narrow strip at the tip of the brush, for a spark cannot take place until the end of the short-circuit period is reached.

The importance of keeping the front tip cool cannot be overestimated, for in it lies to a very great extent the secret of successful commutation. The overload capacity of a machine can be very greatly increased if the brush-tip be kept cool. The metal case in which the brush is usually fitted is not sufficient unless the case almost touches the commutator, and is in very good contact with the carbon.

Since carbon is a very bad heat conductor, any artificial method of cooling must necessarily be deficient, and the best way to avoid a hot tip is to increase the rate of commutation during the early stages of short circuit. This can be effected by the proper distribution of resistance as already shown, or by a commutating E.M.F. The former method, however, has the advantage of greatly increased stability of the brush. When the tip lifts to any considerable extent, as was the case when no cooler was employed, the brush is exceedingly unstable and vibrates considerably. If the brush be high as in an ordinary plunger-holder, or attached to a rigid arm, as in a finger-holder, the vibration may be considerably multiplied.

PART II.—MAGNETIC OSCILLATIONS OCCURRING IN THE MACHINE PARTS.

Section I.—Magnetic Oscillations in the Main Poles.

Fig. 30 gives the E.M.F. waves recorded in coils 1 P to 4 P on the pole-tips. The shape was not found to vary with varying conditions of running, and hence the oscillations may be assumed to be entirely due to the teeth. Table I. (page 515) gives the values of the oscillating flux expressed as a percentage of the maximum flux entering the coil.

The flux entering the coil was ballistically measured for various positions of the armature teeth relative to the coil, and was found to be :—

Coil.	Minimum Flux.	Maximum Flux.
1 P	$1{\cdot}15 \times 10^5$	$1{\cdot}430 \times 10^5$ per turn
2 P	$3{\cdot}40$	$3{\cdot}620$
3 P	$3{\cdot}17$	$3{\cdot}380$
4 P	$1{\cdot}25$	$1{\cdot}305$

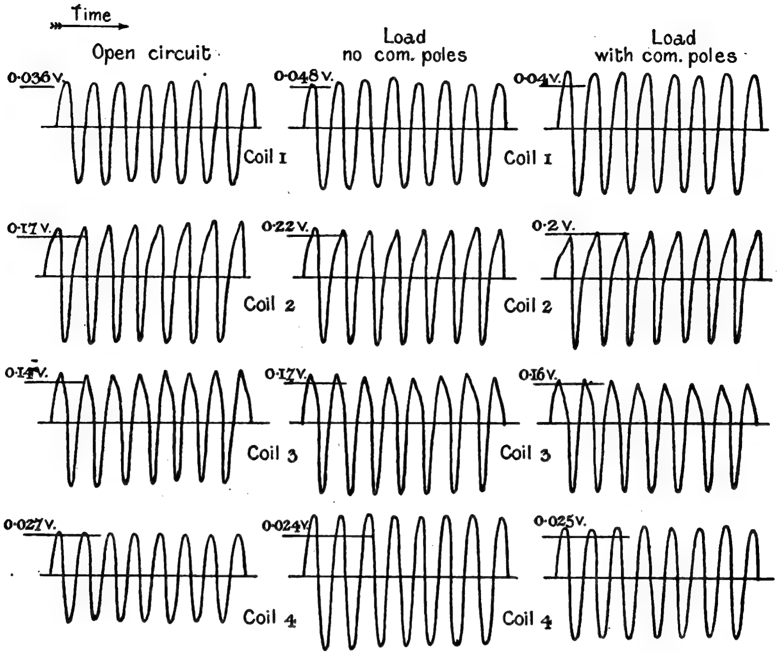


FIG. 30.—Magnetic Oscillations in Pole-tips.

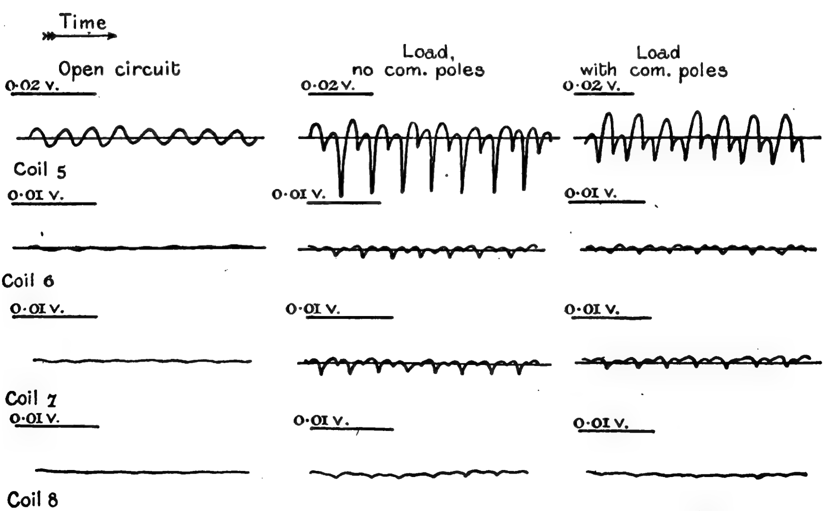


FIG. 31.—Magnetic Oscillations in Pole-shoe Limbs and Yoke.

The load increases the magnitude of the oscillations, especially in the trailing tips.

The presence of the commutating poles increases the oscillations in coils 2 and 3, but has practically no effect on those occurring in coils 1 and 4. This is probably due to the flux from the commutating poles. The "back pressure" of the commutating pole flux deflects the armature reaction flux more into the trailing tip of the main pole, while the commutating pole flux is in turn deflected into the leading tip. The extreme tips being already saturated are not influenced by this action.

As will be seen from Fig. 31, the coils 6 P, 7 P, and 8 P, each of 60 turns, showed but very slight oscillations on open circuit. This shows that only the flux generated by the outer layers near the pole-shoe is influenced by the teeth, and this flux crosses to the armature by way of the pole-tips. On load the oscillations in these coils were

TABLE I.

Flux Oscillations in Main Pole-tips.

Coil.	Percentage Flux.		
	Open Circuit.	Full Load without Commutating Poles.	Full Load with Commutating Poles.
1 P Trailing tip ...	1·40	2·17	2·10
2 P " ...	2·54	3·55	4·35
3 P Leading tip ...	2·10	3·00	3·28
4 P " ...	0·97	1·24	1·25

considerably increased by the presence of the commutation oscillations. Coil 7 P, however, showed a greater increase than coil 6 P. This was due to the path taken by the oscillations, *i.e.*, through the tips and the outer layers of the exciting coil and then back through air, the major portion thus avoiding the solid limbs and yoke. It will be remembered that the coil 6 P was directly on the iron, while coil 7 P was over the exciting coil (Fig. 1).

The actual magnitude of these oscillations on load depends upon the nature of commutation and the position of the brushes relative to the teeth, as has already been explained.

Table II. gives the values of the oscillating flux in coil 5 P under various conditions expressed as a percentage of the flux when the machine is stationary. The flux in coil 5 P, when the machine was stationary, was measured ballistically and found to be $2{\cdot}68 \times 10^6$ lines.

The flux oscillation is considerably increased by load, and is practically uninfluenced by the presence of commutating poles. This shows that although the magnitude of the peak is considerably

TABLE II.

Flux Oscillations in Main Pole-shoe.—Coil 5 P.

	Per Cent. Flux.
Open circuit	0·015
Full load without commutating poles	0·022
Full load with commutating poles	0·022

reduced by the commutating poles, the actual value of the flux change is unaltered. This is due to the fact that whatever be the nature of commutation, the total current change remains unaltered.

SECTION II.—MAGNETIC OSCILLATIONS IN THE ARMATURE.

Fig. 32 shows the flux entering the coils 2 A and 3 A for different positions of the armature when the latter is stationary. The flux

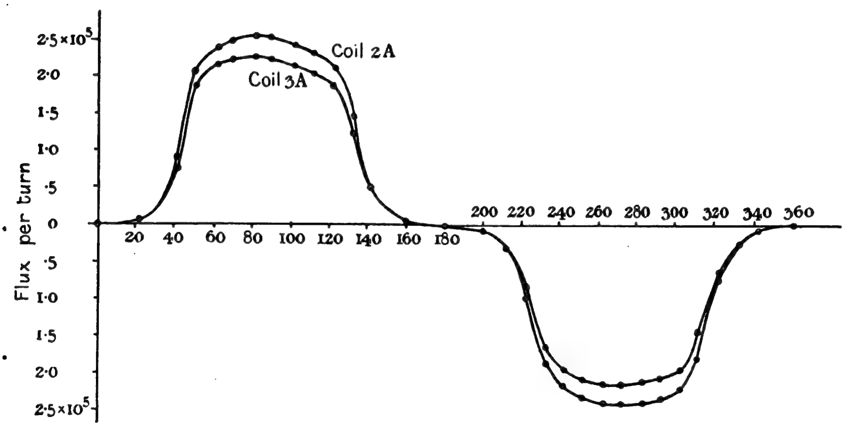


FIG. 32.—Distribution of Magnetic Field round Armature.

entering coil 3 A at the tooth-tip is less than that entering coil 2 A at the middle of the tooth. This is due to some of the flux entering the slot and passing into the tooth lower down than the tip.

The E.M.F. waves recorded in the various coils on the armature under various conditions of running are given in Figs. 33, 34, 35, and 36.

The high E.M.F. induced in the search coils when under the main poles necessitates a somewhat small scale, and the part of the wave generated in the commutating zone is therefore difficult to read. This was obviated by using the slip-ring shown in Fig. 37. The ring was made of wood with two conducting pieces A and B diametrically

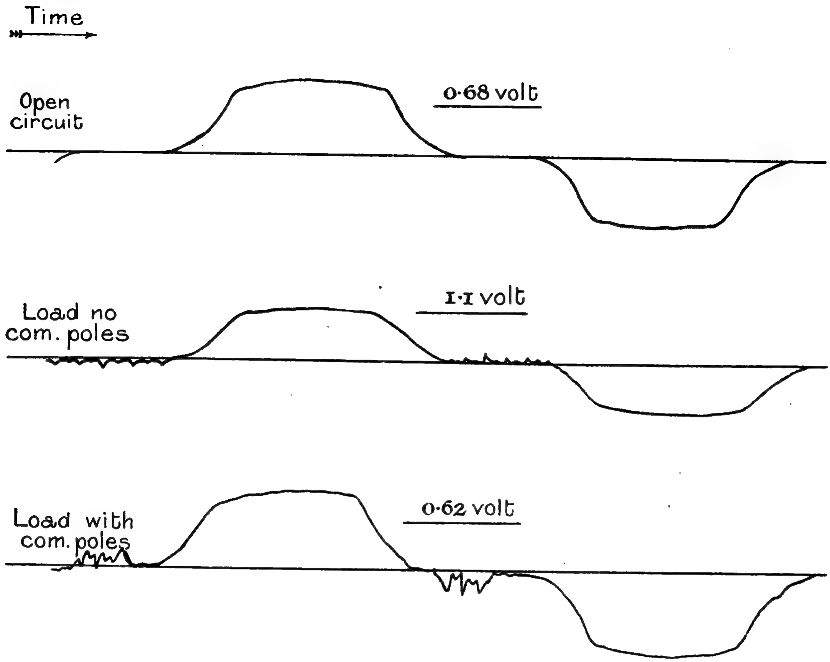


FIG. 33.—Coil 1 A.

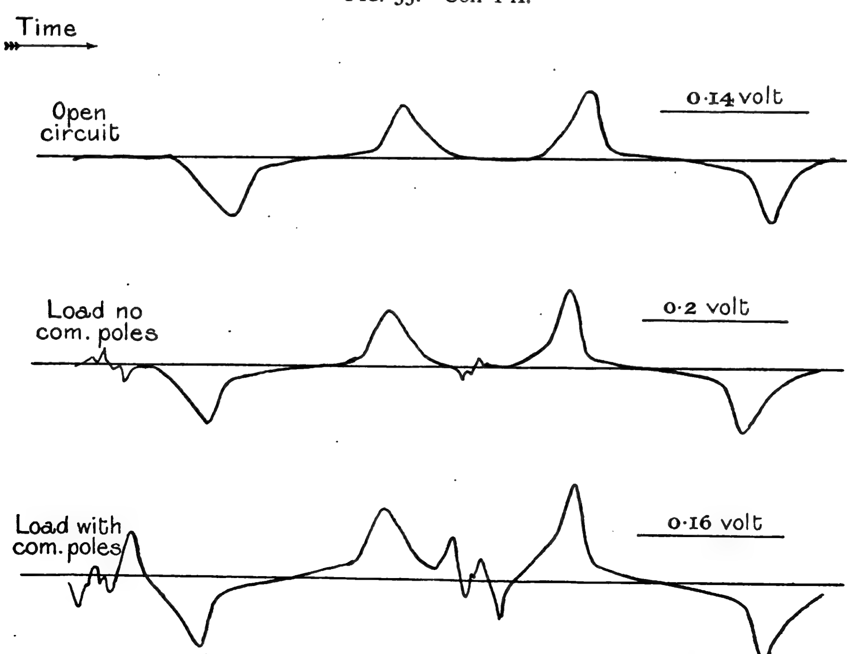


FIG. 34.—Coil 2 A.

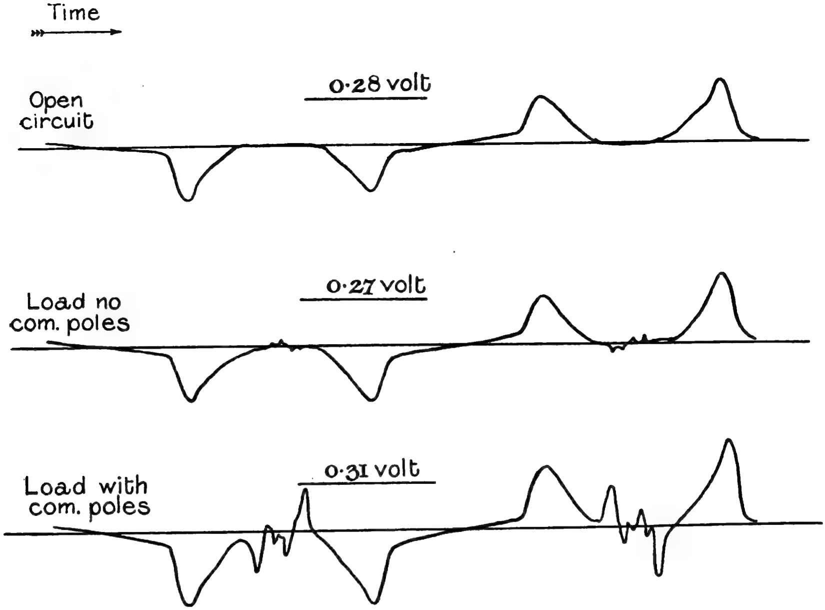


FIG. 35.—Coil 3 A.

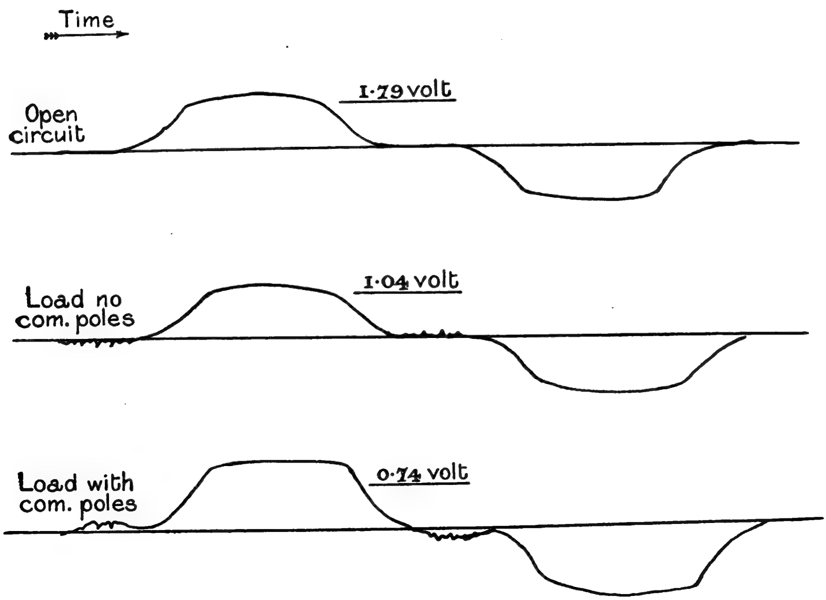


FIG. 36.—Coil 4 A.

opposite to each other. These conducting pieces were connected together and to one end of the search coil, and the ring was set on the shaft in such a position that the circuit was closed only when the search coil was in the neutral zone. In this way the records in Fig. 38 were taken.

The commutation oscillations are very marked in all the records, and the difference in magnitude between alternate peaks due to the positive and negative brushes respectively is clearly seen. No oscillations were induced in any of the search coils in the commutating zone on open circuit.

The E.M.F. peaks induced in coil 1 A gradually increase as it approaches the commutating zone, and diminish again as it leaves it. When the coil is actually in the commutating zone, it links one-half the

TABLE III.

E.M.F. Peaks induced per Turn in Coil 1 A *in the Commutating Zone.*

	Full Load without Commutating Poles.	Full Load with Commutating Poles.
Direction of rotation of coil ↓	0·038 volt.	—
	0·077 „	0·063 volt.
	0·072 „	0·127 „
	0·230 „	0·143 „
	0·097 „	0·063 „
	0·100 „	—
	0·050 „	—
	0·038 „	—

total flux induced by the current in the short-circuited coil, except that portion that crosses the slot below the tip; the E.M.F. peak at this instant is therefore nearly equal to the self-induction or "reactance" E.M.F. per conductor of the short-circuited coil, while the other peaks give the magnitude of the E.M.F.'s induced in the adjacent coils. These values are given in Table III.

The records for the coils 2 A and 3 A consist of four principal peaks, two successive ones in one direction and two in the opposite direction. The first two are produced by the commutation of the top and bottom coils in the slot ahead of the tooth by the positive and negative brushes respectively, and the second two are due to the commutation of the coils in the slot immediately to the rear of the

tooth. Here again the difference in magnitude between the oscillations due to the positive and negative brushes will be noticed.

The remaining peaks are due to the stray flux from the short-circuited coils entering the neighbouring teeth.

The difference between the records obtained for coils 2 A and 3 A shows the amount of flux which crosses the slot between the middle and the tip of the tooth. The left portion of the record for coil 3 A when no commutating poles were employed shows a greater difference between the positive and negative peaks than the corresponding portion of the record for coil 2 A. This is due to the fact that the upper set of conductors in the slot commutated under the negative brush, and the lower set under the positive brush. Hence coil 3 A links all the negative but only a portion of the positive oscillation, while coil 2 A links the major portion of both oscillations.

The right-hand portions of the same records show the opposite effect. For here the upper set of conductors commutate under the positive

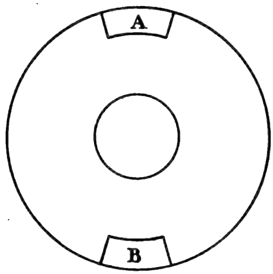


FIG. 37.—Contact Disc.

brush, while the lower set commutate under the negative. Hence coil 3 A links all the positive but only a portion of the negative oscillation, while coil 2 A links the major portion of both oscillations.

SUMMARY OF RESULTS AND CONCLUSIONS.

The principal results obtained in this research may be briefly summarised as follows :—

1. The natural period of the short-circuited coil may be varied by varying its contact resistance, or by properly disposing the resistance over the brush surface (Sections IV. and V.).

2. Sparking depends upon the relation of the natural period to the available period (Sections I. and VI.).

3. The maximum rate of change of the current during commutation may be reduced by reducing the natural period, and at the same time the overload capacity of the machine as regards sparking will be improved (Section V.).

4. The maximum rate of change may also be reduced by accelerating the commutation during the early portion of the short-circuit

period by means of a commutating E.M.F., and this has the same effect as reducing the natural period of the coil (Section VII.).

5. The ampere-turns necessary on the commutating poles may be reduced if the flash across the slot be used to generate the commutating E.M.F. The E.M.F. generated in such a manner possesses approximately the correct wave shape, and the magnetic oscillations

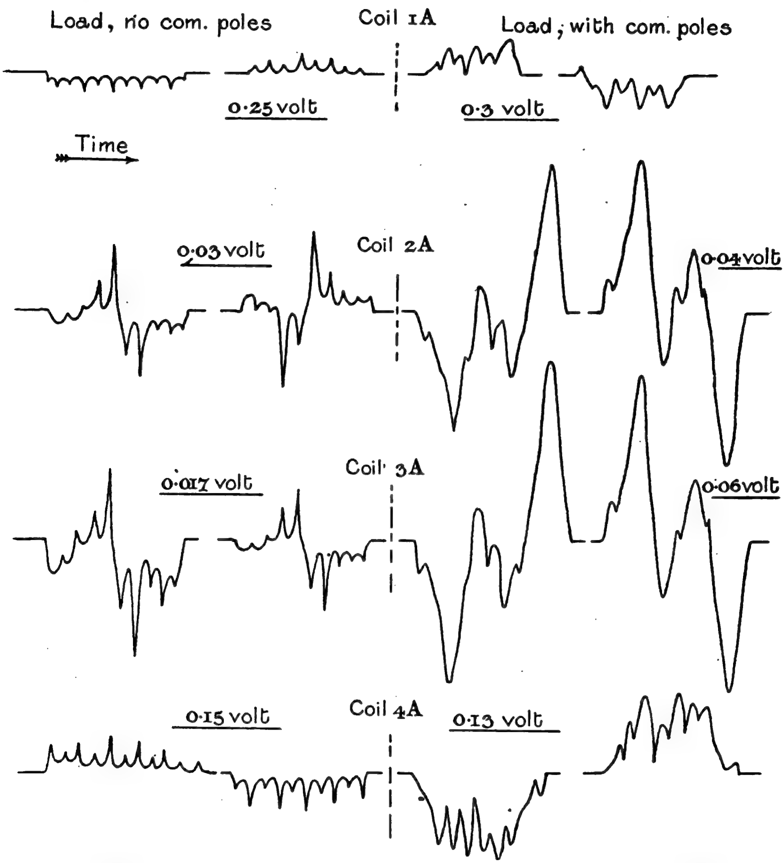


FIG. 38.—Enlargement of Neutral Zone Portion of Armature Search Coil Records.

in the armature teeth during commutation are thereby reduced (Section VIII.).

6. If only one commutating pole be fitted, the ampere-turns necessary are less than when two are in use (Section VIII.).

7. The commutating pole flux fulfils two functions : (1) to generate the commutating E.M.F., and (2) to oppose or press back the armature reaction flux (Section VII.).

8. The negative brush is hotter than the positive; the higher temperature causes the negative to take a higher polish than the positive, thereby reducing its contact resistance. The lower contact resistance increases the natural period, and renders the negative brush more liable to sparking than the positive (Section IX.).

9. The higher temperature of the negative brush causes it to expand more than the positive. The forward tip is generally the hottest part of the brush surface because it is shielded from draughts. The forward tip is alternately heated and cooled as the segments pass under it, and vibrates with the frequency of the segments. This vibration renders the brush unstable and the commutation irregular (Section IX.).

10. The forward tip may be cooled, the vibration avoided, the commutation made regular, and the sparking limit raised by a piece of metal in good contact with the brush at the forward tip and provided with a relatively large radiating surface (Section IX.).

11. The results in 10 may also be obtained by preventing the rush of current at the end of commutation, either by reducing the natural period of the coil or by accelerating the commutation during the early stages by means of a commutating E.M.F. (Section IX.).

12. The vibration of the forward tip of the brush causes a minute arc to be periodically set up between the carbon and the commutator, which causes a brown band to form on the brush and a deposit on the commutator (Section IX.).

This research was carried out at the Technische Hochschule at Karlsruhe, Baden, during the tenure of the Vulcan Fellowship in Engineering, established by the Vulcan Boiler and General Insurance Company, Ltd., at the Victoria University of Manchester.

The author desires to express his indebtedness to Professor Arnold, of Karlsruhe, for the facilities placed at his disposal, and for his kindly interest in the work.

Discussion.

Dr. Kloss.

Dr. M. Kloss: I notice that in the oscillograms there is always a combination of two different kinds of oscillations, one due to the movement of the armature teeth in the magnet field, the other due to the commutation of the current in the coils. I think it would be an advantage to be able to get rid of the first of these oscillations, and this might be done as follows: If a 4-pole lap-wound machine be taken and run with two brushes only in use, then the oscillations induced in a search coil on one of the poles opposite the brushes would contain both sets of oscillations, while that induced in a coil on one of the other poles would contain oscillations due to the movement of the armature teeth only. By connecting these coils suitably it should be possible to annul the one set of oscillations and leave only the oscillations due to the commutation currents. I do not know whether such a method would be possible, but I would suggest it for Mr. Worrall's

consideration. There is another point in connection with the research. Dr. Kloss. Mr. Worrall has used a brush whose width is equal to one segment plus insulation only. Now in practice the brushes used cover more than one segment, and I would like to ask whether the author could give any information as to what happens in this case. Mr. Worrall has in his theory of commutation assumed that the specific resistance per square centimetre of surface of the brush is a constant, whereas actually this is not the case, and I would like to know how Mr. Worrall's results would be modified by this fact. I would like to endorse the remarks about the possibility of improving the performance of a machine by decreasing the contact area of the brushes and increasing the current density. I have known specifications which have stated that the current density in the brushes must not exceed a certain figure, and which left the designer of the machine with the alternatives of either supplying a poor machine in accordance with the specification, or a good one in which the specification was departed from. I think that in preparing their specifications consulting engineers should leave points like this to the discretion of the designer. I would like also to draw attention to the importance of keeping down the temperature of the commutator, both from the point of view of commutation as shown in Fig. 14 A in the paper, and also in order to prevent mechanical trouble due to expansion and contraction of the commutator bars, especially in the case of turbo-generators. This could be done by making the segments hollow and arranging for the passage of air through them, as is done in the Siemens ventilated high-speed commutator which has given such great satisfaction.

Mr. T. F. Wall: Referring to Fig. 31 of the paper, large oscillations were obtained in coil 5, whereas in coil 8 there were practically none. I think that this probably means that they have been damped out by the field winding, and that if the oscillograph had been connected across the terminals of the field coil similar results might have been obtained as were obtained from coil 5. Another suggestion I would like to make is that the damping action of the field coils may, possibly, materially decrease the inductance of the short-circuited coils, and thereby improve the commutation of the machine. I would like to point out that the pulsating flux due to commutation traverses the main axis of the coil and thereby induces in the armature winding an E.M.F. due to rotation, which is in phase with the flux, and therefore with the current producing that flux. If, therefore, records were taken of the E.M.F. induced between the main brushes, the variations of the commutation current might be examined and compared with the records obtained by means of coil 5, which latter show the rate of change of the commutation current. A great deal of discussion has occurred lately as to what really happens in a coil undergoing commutation. It seems to me that, taking a conductor approaching the commutation zone, the lines of force are crowded together behind it and spread out in front. As it passes through the region of commutation, this distribution is changed so that the conductor finally Mr. Wall.

Mr. Wall. leaves with the flux crowded up in front and spread out behind. As the conductor moves along, the lines follow but do not cut it, so that the actual field in which the coil is moving might quite well be zero.

Dr. Arnold. Dr. E. ARNOLD (*communicated*): The influence of magnetic oscillations on the commutation of direct-current machines is often underestimated. Mr. Worrall's elaborate experiments, which he carried out with great ability and perseverance, are therefore of great interest. With reference to the first part of the paper (Section 1), according to my opinion, a commutating field is always necessary in order to compensate the self-induction. Commutation cannot take place in a neutral zone, because the self-induction of the end connections can only be compensated by a field, to which a coil side is subject. The different fields do not coincide, and consequently they do not combine to a resultant field. I agree with the author's remarks about the effect of a brush, the resistance of which increases from the rear tip to the forward tip, but such an increase of resistance occurs also, automatically, with brushes of rectangular section. Experiments have shown that the current density in such parts of a brush that spark is *very small*, and the tension high, thus the contact resistance is very high. Because of very small, almost invisible, sparks at the forward tip the contact resistance per square millimetre of brush surface on this tip may increase to fifty times that at the rear tip, or even more. Bad contact, as a result of sparking, is the cause of this phenomenon. The specific resistance varies automatically between wide limits, preventing too large an increase of the short-circuit current. As long as the sparking is not excessive, the current density is always small. Sparking with a high current-density is so violent that the commutator is damaged very rapidly, and further service becomes impossible. For the above reasons an artificial disposition of the resistance over the contact surface (as in Fig. 8) will not be as successful as one would expect from a theory based on a constant value of the specific resistance. What the author calls *the natural period of commutation*, which must be smaller than the "available period," is not sufficiently well defined. The natural period depends upon the commutating E.M.F.'s, and is consequently a quantity which can be varied with one and the same armature. According to theory* one condition for sparkless commutation is :—

$$\frac{s_T \times T}{a \times L} > 1,$$

where s_T = the specific resistance of the brush at the forward tip; T = duration of short circuit of coil in seconds; a = total surface of brush; L = coefficient of apparent self-induction of coil. Let $T_n = \frac{a \times L}{s_T}$ be the duration of a natural period. The condition for sparkless commutation is then $T_a > T_n$, where T_a = the duration of the available period. For small values of T_a (high-speed machines)

* E. Arnold, *Die Gleichstrommaschine*, vol. i. pp. 405–510.

this condition can only be fulfilled by the introduction of a commutating E.M.F., which compensates part of the self-induction. Mr. Worrall's remarks about the construction of brush-holders and the cooling of brushes are very interesting and important. His experience materially facilitates the design of a good brush-holder. Dr. Arnold.

Results of elaborate experiments on commutation have been published by E. Arnold and F. Jordan in *Arbeiten aus dem Elektrotechnischen Institut der Technischen Hochschule zu Karlsruhe*, 1908–1909, published by J. Springer, Berlin. This paper deals with the influence of the current density, the inconstancy of the specific resistance of the brushes, the actual duration of the commutation, the losses under the brushes, the reaction of the short-circuit current on the main field, and with field pulsations. The inconstancy of the magnetic field is partly due to *pulsations—i.e.*, alterations in the intensity of the field—and partly to *oscillations—i.e.*, to a movement of the field alternately with and against the direction of rotation of the armature. The oscillations are caused by the armature teeth passing the poles, and are described as "flash" and "drag" in a previous paper by Mr. Worrall. Equi-potential connections damp the pulsations of the field effectively but not the oscillations, because the plane of the induced equi-potential loop coincides with the direction of the field. Solid pole-shoes, or, better still, short-circuited windings in the pole-shoes (amortisseurs) damp the oscillations. Such oscillations particularly affect the commutation of machines with a large flux per pole. For such machines solid pole-shoes and a long air-gap are thus to be perferred to laminated pole-shoes and a short air-gap. It appears that the kind of magnetic oscillations and pulsations and also their magnitude depend upon individual features of the machines. They may be very different for two machines of the same design and with the same dimensions. Sometimes a kind of resonance takes place, *i.e.*, the oscillations from various causes strengthen one another; in other cases they may oppose one another. To show the detrimental effect of these pulsations and oscillations of the field, I will mention two cases which came to my notice. The first case relates to a 4-pole direct-current motor of 100 H.P., 220 volts, 1,000 revs. per minute, with 55 slots of $11{\cdot}5 \times 34$ mm., 6 conductors per slot, and 165 commutator bars. Air-gap, 6 mm. The armature is parallel wound without equi-potential connections. The motor has four brush arms, each with five brushes of 19×45 mm. With 200 amperes the motor began to spark violently, and vibrated in consequence of heavy field pulsations. The automatic cut-out disconnected the motor because of a sudden increase of the current; the motor was thus entirely useless. Commutator bars 1–84, 20–103, 43–126, and 63–146 were then connected by four equi-potential connections. The number of commutator bars being odd, only four connections were made on account of lack of symmetry. The result was surprising. The motor was put on load and overload, but no sparking or other detrimental phenomena occurred. The second case relates to a direct-current generator of 550 k.w., 2,400 amperes, 230 volts,

Dr. Arnold. 90 revs. per minute, 20 poles; flux per pole, $9{\cdot}45 \times 10^6$; slot dimensions, $10{\cdot}5 \times 50$ mm.; air-gap, 6 mm. In this machine sparks jump across the insulation of 0·8 mm. between adjacent commutator bars, on which no brushes rested. It proved to be impossible to cure this trouble even after long runs. The pressure between two commutator bars, calculated in the ordinary way, was only 9 volts. Other causes must thus increase this pressure momentarily in order to render the phenomenon possible. The machine is now provided with equi-potential connections (140 commutator bars are connected to 14 equi-potential connections), but has laminated pole-shoes. Thus the field pulsations are damped; and since most probably the phenomenon was due to field oscillations, an effective damping arrangement would suppress the sparks.

Professor Marchant. Professor E. W. MARCHANT (*communicated*): Mr. Worrall is to be congratulated upon having devised a brush-holder which will give consistent results for the surface resistance of brushes. Any one who has tried to make tests of this kind must have realised how difficult it is to get results which agree with one another, and this is shown very well by Fig. 9. The design of this brush-holder is, I think, one of the most interesting points in his paper. With reference to the contact-maker described on page 484, Mr. Duddell and I did a great deal of work with contact-makers about twelve years ago, and we found that the most satisfactory form was one in which two pieces of watch-spring clamped to a piece of ebonite supported on the end of the frame of the machine were short-circuited by a copper piece attached to the rotor. The springs projected radially inwards, and were about an inch long, soldered into brass rods supported in a block of ebonite. This contact-maker is exceedingly simple, and gave excellent results. The emphasis which Mr. Worrall lays on the difference between commutation at a positive and at a negative brush is of great importance; the results he gives for the Le Carbone *Z* brush are considerably modified by current density and by the type of brush. In some tests made in the Electrical Engineering Laboratories of the University of Liverpool by Messrs. Cottle and Rutherford it was found that the ratio of drop in positive brush to drop in negative brush varied within wide limits for different current densities, being greater than 1, equal to 1, or less than 1, according to the current used. These results will, I hope, be published shortly, so that I will not refer to them at greater length here. The arrangement described by Mr. Worrall on page 510 is not very clear; he says, "The carbon brush was placed on a thick piece of brass and bedded down on it by several thicknesses of copper foil." Does this mean that the copper foil came between the brush and the brass?

The greater sensitiveness of negative brushes to variation in temperature, current density, etc., has, I think, been frequently noticed, but Mr. Worrall's method of getting rid of chattering is most ingenious. It seems almost incredible that changes in temperature of the brush could be sufficiently rapid to cause chattering, and I should like to

ask Mr. Worrall whether he is quite certain that the result obtained was not due to a mechanical effect caused by the addition of the copper and copper foil to the brush. The copper foil was insulated from the carbon by mica, and this material, of course, besides being a bad conductor of electricity, is also a bad conductor of heat. The effect obtained is most remarkable, and the results should prove of great interest to those of us who are troubled with chattering brushes. **Professor Marchant.**

The phenomenon Mr. Worrall set out to investigate is one of the most complex in the whole region of electrical engineering, and the results he has recorded should prove of great value. They have succeeded in throwing new light on a problem which even now is obscure and difficult.

Professor Robertson. Professor D. ROBERTSON (*communicated*) : Mr. Worrall's paper draws attention to some most interesting phenomena in connection with commutation, particularly the different behaviour of the positive and negative brushes, and the mechanical vibrations due to local heating. I think, however, that Mr. Worrall has made the theory of commutation appear needlessly obscure. The following is the method of putting it which I have adopted for years, and it seems to be much more simple than that given in the paper.

During the time that a coil is short-circuited by the brush, the current in it has to die away and a new one to grow in the opposite way. If it has exactly the proper value at the instant the short-circuit ceases, the current in the segment leaving the brush will be zero, and there will be no spark on breaking contact. If it has not reached that value, or if it has grown too large, there will be a current in the old segment, which, since the current in the coil refuses to change instantly, continues to flow in a spark after the brush has left the segment. This is the spark that does most of the damage and is the *only* spark possible if the brushes are making perfect contact. The condition for the avoidance of this spark is the simple one that there shall be no current in the old segment at the instant it leaves the brush, and it does not greatly matter how the current has changed during the short circuit so long as this final condition is satisfied. Any other sparks at the brushes can only be caused by faulty contact between the brush and segments due to bad surfaces, or to mechanical vibration caused by unsuitable brush-gear, or by the thermal effects referred to by the author. The sparking at the rear tip mentioned at the bottom of page 491 must be due to these causes: sparking takes place at the forward (breaking) tip whether the commutating E.M.F. is too small or too great. The inductance of the coil opposes the change of the current and is the prime cause of the trouble. The mutual inductance between adjacent coils simultaneously undergoing commutation is also a good second, particularly when they are in the same phase at the same instant. The resistance of the coil itself and of the lugs helps to kill the old current, but also hinders the growth of the new, and so does not produce much direct effect on the commutation of continuous-current machines. It is, however, useful, and even

Professor Robertson.

necessary, in alternating-current machines as it reduces the short-circuit current caused by the transformer E.M.F. In all cases it reduces the effectiveness of the brush contact resistances by diminishing their ratio to the total, and to that extent it is harmful. Brush contact resistance promotes the change of current because it is gradually shifted from the new segment to the old one. If its effect were so large as to make all the other negligible, the current entering each segment would always be proportional to the area of contact on that segment (assuming uniform contact resistance) and the commutation would be a straight line or a series of straight lines according to the width of the brushes. This distribution of the current, which may be termed the natural one, gives smaller contact losses than any other. Actually the inductance E.M.F.'s are not negligible, and the current departs from this distribution and the losses are increased. To counteract the inductance E.M.F. a *motion* E.M.F. is induced in the short circuit by giving the brushes a lead in the right way, by adding commutating poles, or by putting special coils between the segments and main winding (Sayers). Commutating poles are the most effective, because they can be excited in series with the armature and their effect made proportional to the work to be done. Many problems could be much simplified if we could get away from some of the conventions of our predecessors, such as the addition of fluxes instead of the excitations producing them. The author's explanation of the action of the commutating poles (page 505) gives an example. The commutating pole reduces the resistance in the path of the armature cross-flux, and would therefore increase that flux if the commutating poles were not excited. But the excitation required to balance the armature reaction is not affected by that fact, and would be exactly the same whether the commutating pole were made of iron or of wood. The commutating pole coil must have sufficient *additional* excitation to magnetise it and the air-gap and teeth to the degree necessary to induce the required commutating E.M.F., and this additional excitation is, of course, very much smaller with an iron core. The "relative movement" idea of statement 1 on page 492 (see also page 486), is a rather dubious one, as the two induced E.M.F.'s are of quite different natures. The commutating flux is approximately fixed in space and acts only on the sides of the coil which cut it by their motion. The inductance flux is linked with the whole coil, moves with it, and changes in amount when the *current* changes. It then acts on the ends as well as on the sides. The one E.M.F. is due to change of position and the other to change of current. The inductance E.M.F. corresponds to the storing of energy in, or the taking of energy from, the magnetic strain of the surrounding medium, and this energy moves through space with the coil. The motion E.M.F. corresponds to the taking in or giving out of mechanical energy by the current. During the first, or decay, portion of the short circuit the current is, or at least ought to be, taking back this stored energy and giving out mechanical energy; the short-circuited conductors have forces acting on them in the way of the motion and are therefore motoring. During the second

Professor Robertson.

part, while the reverse current is growing, the current is re-storing the energy in the medium while it receives mechanical energy. The forces now act against the motion and the conductors are generating. If the compensation were absolutely perfect, the rate of receiving energy of one kind at any instant would be the same as the rate of giving out the other kind, and none (neglecting the resistance losses meantime) would have to be handed over to or received from the rest of the circuit. Such perfect compensation is neither attainable nor necessary. It is sufficient if the current has not to give out or take in an appreciable amount of energy just as the segment is leaving the brush. The mathematical theory on page 488 and the brush shape deduced from it are not of much real value, for the conditions assumed are not those usually found in practice, and several important factors have been left out of account altogether. It is seldom that the brushes are as narrow as one segment width. The mutual inductance of the neighbouring coils being commutated at the same time, even when the phase of commutation is not the same for both, is only a little less important than the self-inductance of the coil itself, and the resistance of the coil and lugs is not usually quite negligible.

The author's "natural period" is a rather indefinite sort of thing. With inductance only, the current would never commutate of itself; while with a brush contact resistance only it would always do so exactly in the available period; with commutating poles it is rather a certain displacement across the poles that is necessary to produce exact commutation than a certain time. What, then, is the "natural period," and how is it measured so as to enable the various statements that are made about it in the paper to be justified? Even the "time constant" of the circuit (inductance ÷ resistance) has hardly a definite meaning here owing to the change both of the inductance and of the resistance of the short circuit as commutation proceeds. It is doubtful, however, whether they give much information as to the process of commutation itself, beyond indicating the maximum rate of change of current, and even that is marred somewhat by tooth ripples. The usual way of applying the oscillograph to show the armature current by splitting a coil and adding the oscillograph shunt though slip-rings is of little use, as the behaviour of the current must then be very different from that under normal conditions. In 1903 I devised a method of making the armature coil itself act as the shunt, by which means the phenomena may be studied without changing the conditions of the armature coil by more than 1 or 2 per cent. I had the attachment put in a machine which was at the time at the makers for alteration, but owing to the lack of an oscillograph then, and the unfortunate fire at the Merchant Venturers' Technical College, Bristol, just before the oscillograph arrived, the intended research was suspended for a time and is now only in its preliminary stages. The principle used is exactly the same as has since been applied by Campbell to the design of non-inductive shunts. The method has been used with the tracing desk outfit, the only one at present available,

Professor Robertson.

for class demonstrations during the past three sessions, with most instructing results. It has shown us that our brushes are too wide, and shows most interesting peaks when they are moved away from the best position. The effect of the mutual inductance is also marked. This machine has also a coil like the author's 1A, but wound in the bottom of the slot, which is a little deeper than the others. The curves it gives differ considerably from those on page 517: the tooth ripples are very pronounced, while the commutation splashes are both larger and more symmetrical.

Dr. Thompson.

Dr. SILVANUS P. THOMPSON (*communicated*); Mr. Worrall's paper seems to me one of the most important contributions that have been made for some years to our knowledge of commutation. He has with great success applied the method of the oscillograph to unravel the extremely complicated phenomena which occur at the commutator of every dynamo or motor; and, if he leaves a good many points still to be investigated, we ought to be very grateful to him for having already unravelled so many of those complications. Dealing first with a practical point, let me praise the particular work on the irregularities of commutation which he traced to the surface irregularities of the commutator and the vibration of the brushes, leading him to the invention of a new type of brush and brush-holder, which will probably find a much wider application than in a mere experimental machine in the laboratory. Also his advice to plough out the lines of the mica insulation as they appear at the surface of the commutator is wholly good. I have for many years found this treatment to improve the commutation in doubtful cases. When I first looked at Mr. Worrall's paper it seemed to me that it was a pity that his chief work had been carried out on a machine in which, from its design, with an odd number of commutator segments, commutation did not occur simultaneously at the positive and negative brushes, and indeed in this respect the case chosen for the research is not representative of the majority of continuous-current generators. But on further reading it would seem that this feature had, for the purposes of the research, been of advantage, as it separated the effects due to commutation at the positive brush from those at the negative brush. This part of the research is very instructive. The results emphasise the analogy that exists between the processes going on in the contact resistances beneath a carbon brush and those going on in an arc lamp. In both cases there is found a resistance which decreases with the current density, and in both cases the resistance is greater for currents leaving carbon than for currents entering carbon. The passages relating to the shaping of the carbon brush to give greater resistance at the forward tip are both instructive and convincing. They justify the old practice of using carbon tips to copper brushes, or the use of combined sets of brushes, in which one carbon brush was set in advance of the row of copper brushes. Equally important, it seems to me—and it should be of great practical value—is the suggestion to furnish tips of all carbon brushes with cooling appliances of metal. Altogether this is a noteworthy paper.

Mr. W. ARMISTEAD (*communicated*): The paper has interested me very much; the author has attacked the problem of commutation from a practical point of view, without encumbering the matter with theoretic details. To my mind the theoretic considerations of commutation are quite burdensome, and it is only by attacking the subject practically that it is possible to come to any results which are likely to be of any use to the manufacturer. It appears to me that the machine on which the author carried out his experiments was very large for the output, the armature being 10 in. in diameter, and the iron 6 in. in length. When my firm were building 2-pole machines for such an output, we should not have used an armature more than 6 in. in diameter, with $4\frac{1}{2}$ in. length of iron; then it would have 624 conductors. I believe it is only on conditions of very light loading that it is possible by means of over-excitation of the auxiliary pole to obtain a transference of the sparking from the toe to the heel of the brush. The author makes an interesting remark with regard to the reduction of the area in contact between the brush and the commutator. He observes that there may be an actual reduction of temperature when the area is reduced. The experience of my firm bears this out, though so far as sparking is concerned, we have not found that dividing up the brush by means of a slot or slots parallel to the shaft has been of any use. Large brushes appear to be almost useless—no doubt, largely, owing to the bad conductivity of the carbon and the impossibility of radiating the heat. The contact between two surfaces such as the brush and the commutator cannot be made at more than three points for each brush, no matter what size. Mr. Armistead.

I wonder if the author knows Mr. R. V. Marshall's brush and holder. Bearing these points in view, this design of brush-holder is only $\frac{1}{4}$ in. long along the axis of the commutator. We have tried this arrangement in practice, and find that a larger current can be collected per brush with the smaller brushes without an increased rise in the temperature either of the commutator or of the brushes; this small brush will collect practically the same amount of current as one four times the dimensions. Unfortunately, practical difficulties come in the way of its universal adoption. The experiments the author has made with regard to the differences between the positive and negative brushes with regard to collection are very instructive. We had often observed it, but had not traced it down as the author has done so clearly. The author speaks of the increased inductance in machines fitted with commutating poles. It always appears to me that this is very much exaggerated. To begin with, the commutating poles are for the most part solid, and the very high periodicity of the fluctuating currents which occur in their vicinity precludes the possibility of any serious conduction of lines of force through this path. I have not been able to test the matter experimentally as the author has done with an oscillograph, but have found that facing poles with sheet copper, and surrounding them with a stout band of the same material does not make the slightest difference so far as sparking is concerned. Of course, if

Mr. Armistead. the commutating poles are not excited properly, there is bound to be a large amount of magnetic leakage when the armature is generating or receiving current owing to the displacement of the neutral magnetic zone on the armature relatively to the yoke. I should like to know if the author could tell us why it is that the *contact* resistance between the carbon and the copper of the commutator is reduced by an increase of temperature.

Mr. Hawkins. Mr. C. C. HAWKINS (*communicated*): The question of whether the self-induced E.M.F. in the case of satisfactory commutation exists, and is compensated for, or is rendered non-existent, resolves itself finally into the question of what is the actual physical field in which the short-circuited coil moves. Mr. Worrall's analysis, resting upon the component fields and planes normal to each other, does not at first sight seem to give clear guidance, owing to the great complexity of the actual practical case of the slotted armature. It appears to me that a resultant commutating field must always be present at least in such amount and density as to compensate for the inductance, self and mutual, of the *end-connections*; for the flux linked with the latter follows a path entirely different to that of flux entering or leaving the surface of the core. The remainder of the inductance of the short-circuited coils may be resolved into a certain amount due to lines crossing the air-gap, and a certain amount due to the bending of the final field within the slot and about its neighbourhood. The former part is cancelled by opposing lines, so that it becomes non-existent in the resultant field. The latter part will call for some commutating flux sufficient to counterbalance the rate of change of bending of the actual lines so far as they cut the armature coils, the reason being that the M.M.F. of the commutating poles will never by itself straighten the distorted lines near the coils within the slots, so that the third part of the inductance cannot be strictly annulled but must be compensated for. Although the distinction between the material and the available period of commutation is up to a certain point useful and valid, yet it contains an element of indefiniteness which rather limits its usefulness. What is a sufficiently close approximation to the final value to warrant us in regarding the time in which it is reached as the natural period? And if we are successful in obtaining a natural period appreciably less than the available, then the difficulty arises of keeping the current at the required value during the remainder of the available period. The above criticisms which suggest themselves on first reading Mr. Worrall's most interesting paper might, however, yield to a further study of it. The shape of brush toe recommended by the author may be compared with the serrated edges which Mr. Carter * recommends from an analogous point of view, viz., as valuable in unfavourable cases for keeping the current density at the last moment finite.

Mr. Moffett. Mr. F. J. MOFFETT (*communicated*): I have been greatly interested in Mr. Worrall's paper, more especially in the section treating of the difference in behaviour of the positive and negative brushes. A case

* *Electrical World*, vol. 55, p. 784, 1910.

of this sort recently came under my notice. The machine was designed for an output of 1,000 amperes at a voltage of 80 and a speed of 700 revs. per minute; it was provided with commutating poles. The brushes used consisted of a mixture of copper dust and carbon (Morganite Link 2/538), the current density being 85 amperes per square inch. When running at full load, the commutation at the positive brushes was very good, but trouble was experienced at the negative brushes. The wearing surface of the negative brushes not only showed the brown bands mentioned by the author, but the copper was removed, leaving the carbon alone. With an overload of 20 per cent., or 1,200 amperes on the machine, the commutation at the positive brushes was still fairly good, but at the negative the sparking became so vigorous as to make it impossible to continue the run. The removal of the copper from the negative brushes was even more marked at the overload than at normal full load, and the brushes became extremely hot. In order to remedy this trouble it was decided to substitute soft carbon (Morganite Link 1/289) for the copper-carbon brushes on the negative poles, although these were, naturally, of high resistance. The effect of the change was remarkable; not only was the commutation at normal load almost perfect, but even at 1,200 amperes there was no serious fault to find, and the alteration was quite successful in permanently curing the trouble. Mr. Moffett.

From an examination of the copper-carbon brushes on the positive and negative poles respectively, there appeared to be some justification for the assumption that the copper was carried along by the current by a kind of electrolytic action, but it is possible that the temperature at the contact surface of the negative brush reached so high a value as to render the copper molten, in which state it was carried away by the commutator segments. In support of this explanation I may mention that in the space between the commutator segments there was a considerable amount of copper which did not appear to be derived from the commutator bars.

Mr. H. G. STEPHENS (*communicated*): I should like to express my appreciation of this valuable paper, and would suggest that the experiments be carried out further. For instance, the case when only one coil is short-circuited is the simplest possible case and is comparatively rare in practice. Regarding equation (1) on page 488 it appears to me that this is incomplete even for the purely hypothetical case considered. If r represents the resistance of the one coil, I think the equation should be— Mr. Stephens.

$$E = i\,r + L\frac{d\,i}{d\,t} + r_2\,i_2 - i_1\,r_1.$$

It this is so, the shape of the ideal brush curve in Fig. 7 would apparently be altered. Further, I would point out that straight-line commutation is not always a desideratum, as in the case of high-speed machinery, *e.g.*, turbo-generators; accelerated commutation is sometimes found to give better results.

Professor Baily.

Professor F. G. BAILY (*communicated*): Both the methods of experiment described in this paper, and the results obtained, are of great interest, affording a deeper insight into that most complex problem, the phenomena of commutation. As the paper deals with a subject, considered from a different point of view, previously treated in my paper in the *Journal*,* the result of the one may be considered in the light of the other.

The author begins with a novel calculation of the best shape of a brush, and arrives at a result which I used to believe ought to be advantageous. In my hands, however, it did not produce any improvement, as measured by the sparking E.M.F. or potential difference between brush and segment at the moment of separation. I attributed this to the law of variation of the contact resistance between carbon and copper. As this continually diminishes as the current increases, ultimately varying almost inversely as the current, restriction of area has much less influence on the total resistance than would at first sight appear probable. In consequence I do not think the mathematical formula, which assumes s, the contact resistance per unit area, to be constant, can be accepted seriously. I am aware that Professor Arnold has shown that for alternating currents s is nearly constant, and he has concluded that this value would apply to the rapidly changing condition under a dynamo brush. But, as I have shown in my paper (*loc. cit.*), the current density at any one point in the brush surface during commutation does not fluctuate much, and further, the product, current $\times$ resistance, hardly rises above 1·5 volts, however high the current density.

A possible explanation of Mr. Worrall's experience, that a brush with the inside part cut away does improve matters, brings me to another point. He suggests that an important cause of sparking is a vibration set up by the momentary heating and expansion of points, causing a sudden rise and subsequent fall of the carbon. This is our old friend the Trevelyan rocker, and it seems to be a very instructive explanation. It affords a reason for the sparking at the leading edge of the brush, which has always been a difficulty to me. That the few volts available could possibly strike an arc to the oncoming segment is unthinkable. But directly contact is made, those available volts produce an enormous rush of current at points along the thin line of contact, which throws the brush into the air and draws an arc. As the brush advances along the segment things become quieter, and no further rocker action takes place. Hence only the oncoming edge of the segment is pitted, as is the case.

Now, all sparking due to vibration (and sparking generally is due to vibration) can be reduced by increased and steady pressure. By cutting away the brush in the middle, not only is the pressure per unit area increased, but the bearing on the trailing or forward edge is greatly improved. I myself found good results by cutting a cross, square across the carbon face, leaving four feet, one at each corner.

* "Some Phenomena of Commutation," *Journal of the Institution of Electrical Engineers*, 1907.

Professor Baily.

Probably a three-legged brush would be still better, one at the forward edge and two at the back. Hence I am inclined to doubt that Mr. Worrall's experimental results confirm his mathematical reasoning. Some of my own experiments followed the formula more closely, for I used a triangular brush with the apex trailing. This would not diminish the rocker action, and did not, in fact, improve matters at all. Indeed, the narrowing of the forward end would increase the rocker action, owing to the concentration of current and heating, and this might neutralise the beneficial effect of throttling the current. Subsequent to the reading of my paper, in some further work on the subject I came to a hollow brush much like Mr. Worrall's, with the idea of obtaining improved bedding at the edge, but the interruption of the experiments prevented my testing this arrangement.

Mr. Worrall's method of examining the commutation is very ingenious and sound. It has, however, the disadvantage of yielding a rather cryptic result, as the tooth ripples and waves from two opposite brushes are blended. With a multipolar machine there would be ripples from the brushes on both sides, *i.e.*, the two adjacent brushes of similar sign, as they both control the current in bars lying along the side of the pole under test. I know that in the experiments referred to, when I was examining the current in a search coil round the pole-shoe of a large multipolar machine, the curves obtained were more complex than those in the paper, and when the machine was made to spark the curve showed extraordinary irregularity and jaggedness, such as to defy analysis. Still the simplicity of the method has great advantages, for even without the timing contact-maker much can be learnt by a simple search coil and oscillograph, if one is practised in interpreting the curve.

The marked difference between the positive and negative brushes is unexpected, and I am not quite satisfied with the explanation given, that it is due chiefly to the different temperature coefficients of the positive and negative contact resistances. In the curves of Fig. 20 it appears that a shift of three segments was required to equalise the conditions. Not long ago I was examining the change of temperature of the surface of the commutator as it passed the brush, and though the rise was quite distinct, it was not a great deal. For instance, with an average value of 40° C. for the surface, there would be a difference of some 10° C. between the front and back surfaces as the copper passed the brush. This seems inadequate for the effect produced, and, of course, the carbon surface maintains a fairly uniform temperature at any one point, though one brush may be permanently hotter than the other.

A natural objection to this great difference would be that such a marked diversity would have been noticed in practice long ago. We are certainly familiar with the sight of one brush sparking and the other not, but that occurs also in a single brush of a multipolar machine, and may be due to many things. But I do not regard this objection as valid. After much experiment on commutation one begins to wonder how

Professor Baily.

any machine runs without sparking, and then one realises how powerfully the brush overrides small deviations from the perfectly regular change of current. The carbon brush covers and hides a multitude of the sins of the designer.

This method of analysing commutation appears to me to have one theoretical objection, in that it gives preference to the straight-line change of current. An earlier commutation can be obtained without any serious reverse currents at the end, as I showed in my paper, and this early commutation obviously gives a margin for overloads. I believe it would be difficult with a multipolar machine to distinguish how far early commutation was occurring, whether with reverse currents, and all the numerous possibilities. Mr. Worrall seems convinced that reverse currents are rare, and possibly in his machine they were slow in occurring; but that was not my experience in larger machines.

In concluding this long contribution to the discussion, I wish to express my appreciation of the paper. It has dealt with a most complex set of phenomena in a powerful manner, and has materially helped with a question of immense importance. Now that forced draught is raising the output per unit of weight of a dynamo, the commutation limit will again come to the front, and brushes form the next useful advance in dynamo design. But before brushes can be improved, methods of testing their real action and influence are essential.

Mr. Worrall.

Mr. G. W. WORRALL (*in reply*): The suggestion of Dr. Kloss regarding the possibility of cancelling the tooth oscillations would only be practicable in a machine of perfect workmanship and material, and in a commercial machine of to-day this standard is never reached. Mr. Wall's method of utilising the armature for observing the magnetic oscillations (enlarged upon in a letter to the *Electrician*, Coales and Wall, May 27, 1910) has many points in its favour, but is not quite so simple and free from complication as the search-coil method. For, as Mr. Wall states (see letter), the results involve the interference of E.M.F. variations due to the number of commutator segments being finite. Such variations will be exhibited in each type of oscillation recorded, and in addition to this there will be a similar variation in the main E.M.F. of the machine. The former may possibly be of too small a magnitude to seriously influence the results, but the latter will be quite appreciable. The method is further open to the objection that the brushes must remain in the neutral plane, and hence no very extensive experiments in practical working can be carried out. Still the great advantage which the method possesses of the ordinate in the record being proportional to the current should render it at least a valuable check on other methods of research. If, however, Mr. Wall can overcome the difficulties the method should prove a valuable asset to the investigator. I did not investigate the damping effect of the field coils, but previous experience with laminated poles leads me to believe that the damping was mainly due to the solid pole-pieces. I have been very interested to hear so much to confirm my observations on the positive and negative brushes. Mr. Moffett's experience is particularly interest-

ing. Some misconception appears to have arisen concerning my remark that a reduction of brush area might cause a reduction of temperature. I do not refer to a full surface brush with a reduced area, but to a divided brush such as Fig. 8. Here the reduction of temperature effected is not so much due to a reduction, as to a better disposition of the contact area. The improvement in running effected by the metal strips on the brush tips could not be due to any mechanical cause, as Professor Marchant suggests, for if such were the case, one would expect no difference in running to take place on changing the polarity of the brush. Mr. Armistead's question why the contact resistance is reduced by an increase of temperature is partly answered on page 508, where I state that one effect of temperature is to cause the brush surface to take a polish, which will naturally have a lower contact resistance than an unpolished surface. The remainder of the answer is probably associated with the fact that carbon has a negative temperature coefficient, although such a statement does not carry one much further. Some criticisms have been made regarding my mathematical theory of commutation and the brush shape deduced. Mr. Stephens considers that the term $i\,r$ should be included in equation (1); this is quite correct, but its influence is only slight, as r is only small compared with r_1 and r_2, and I intentionally omitted it in order to render the mathematical process sufficiently simple. No mathematical theory, however complex, can be said to even approach accuracy, and the only value of such theories is to suggest the existence of unknown phenomena, or the explanation of those already discovered. This latter function is certainly fulfilled by the theory given in the paper, and I cannot see any justification for Professor Robertson's remark that it is not of much value.

Mr. Worrall.

My analysis of the rival theories of commutation was not intended to convey my own views on the subject, as these are fully dealt with later in the paper, but rather to show that there was some ground common to both sides. One side is, as is well known, led by Professor Arnold, and I am glad to find that we have the advantage of Professor Arnold's own remarks on the subject in this discussion. Professor Arnold states that an external field is necessary to compensate the self-induction of the end connections of the coil. Such an external field must be in the region of the coil side, and will generate an E.M.F. in the coil, while the self-induction field of the end connection will be beyond that region. Compensation is therefore, Professor Arnold states, impossible. But is it legitimate to consider such comparatively small fields as entirely separate from the main fields? I think not; I prefer to consider the entire external field and the entire self-induction field of the coil, and these may be said to be in the same region, and therefore possible of composition. There will, further, be some stray flux from the external field in the region of the end connections. I fully realise, however, that such considerations by no means give a full picture of the commutating zone, and Mr. Hawkins' very clear statement of the case is much nearer the mark, but if such complication

Mr Worrall.

were entered into, a parallel analysis of the two ideas would scarcely be practicable. For my own part I prefer not to regard any cancelling or compensating of either fields or E.M.F.'s as taking place, for in the case of the fields, the presence of the air-gap will cause the two opposing fluxes to spread out, hence both will be in existence, while E.M.F.'s which are varying in totally different ways can only cancel each other at a particular instant, and hence such a conception is rather futile. Further, the important function of the external E.M.F. is to accelerate commutation during the early stages of the short-circuit period, and if this takes place, the end of commutation will be perfectly satisfactory. The end of commutation described by Professor Robertson is in exact accordance with my own views as given in the paper, the only point of difference between us being that Professor Robertson considers that it does not greatly matter in what way commutation takes place, so long as it finishes satisfactorily, while I regard the manner of commutation as being of very great importance in that it is the manner of commutation that determines the final condition. The manner of commutation has also a bearing upon the losses, for the less the rush of current the less will be the heating of the brush surface and commutator, and also the less will be the magnetic oscillation and consequent magnetic losses. I cannot agree with Professor Robertson that sparking at the rear tip of the brush is only due to some effect other than an excessive commutating field. Sparking at this tip may be due to other causes as well, but I have no reason to think my observation and explanation incorrect; sparking alone at the rear tip exists only for a very small range of the commutating field, and sparking at the forward tip immediately follows, and consequently the critical point might easily be missed. I have recently had my observations on this point confirmed by works test-plate engineers. The idea of the natural period is of necessity somewhat indefinite, for the process of commutation would not really be complete until the end of the available period. The natural period cannot be calculated, but is of the nature of a conception which I have found exceedingly useful in explaining many of the phenomena observed. I feel very much interested in Professor Robertson's method of commutation research, and I hope that he will publish some oscillograms in due course.

The illustrations given by Professor Arnold of the effect of equipotential connections on the sparking are very interesting, and I am in full agreement with him that the magnetic oscillations play a much more important part than is usually supposed, for in the majority of papers on the phenomena of direct-current machines it is stated that these oscillations are entirely damped out. Mr. Carter's brush, to which Mr. Hawkins has drawn attention, is somewhat on the same lines as Professor Kapp's, but in my opinion it does not fulfil the necessary conditions that the contact resistance in the forward segment shall be high during the *early* stages of the short-circuit period. The serrated edges are, I think, as Mr. Carter claims, only effective at the close of the period. I was not acquainted with Mr. Marshall's brush-holder,

Mr. Worrall.

but Mr. Armistead has kindly supplied me with further details. The question of the three points of contact per surface is a very important one, and Mr. Marshall's experiments appear to bear this out. An examination of the majority of brush surfaces will reveal the very small area of contact that they really have; the whole surface may be polished, but that is caused by slight changes in the position of the brush. Such changes take place in all ordinary brush-holders, and are the cause of the uncertain and irregular commutation usually obtained. In reply to Professor Marchant's question regarding the apparatus used for the temperature experiments, the copper foil was placed between the carbon and the brass.

Professor Baily appears to suggest that the expansion and contraction I observed takes place in the copper rather than in the carbon, and that the brown band which is formed on the brush surface is not so much due to the carbon lifting from off the copper as to the copper sinking from under the carbon. I take it that Professor Baily does not dispute the fact that *if* the expansion and contraction take place in the carbon the entire series of phenomena described would naturally follow, and hence all that need be considered is whether the brown band could be formed on the brush surface by an expansion and contraction of the copper. Any action that takes place must be a purely superficial one; in the case of the brush, a concave surface heated from the concave side straightens out, and in the case of the copper, a convex surface heated from the convex side would become more convex; in both cases therefore the resulting phenomenon of a break of contact would occur. But now consider the remedial measure that was successfully applied, *i.e.*, the cooler; would the metal strips at the tip of the brush cool the commutator segment? I think not, and hence I think it must be conceded that the action takes place in the *carbon* rather than in the *copper*.

Professor Baily's suggestion that the success of the divided brush is due to mechanical considerations cannot be entirely repudiated, for a brush with a divided surface must necessarily make better contact than one with a full surface, but I do not think that such a series of curves as is given in Fig. 16 would be obtained if good contact were the only reason. Besides, perfect contact was obtained with the full surface brush, as is shown by the uniformity of the curves, and commutation under the positive brush was adversely influenced by the division. The 10° C. difference mentioned by Professor Baily is, I take it, for the commutator, but this would be very much greater for the carbon, as according to my experience over a large number of machines the carbon is always very much hotter than the commutator.

I do not quite understand Professor Baily's remark that my method of analysing commutation gives preference to the *straight line* change of current, except he means that the method would be exceedingly difficult to apply to any other law. In this he is quite right, and it was for that reason I assumed the *straight-line* law, but, as I have stated elsewhere, I do not consider that mathematical theories of commutation,

Mr. Worrall.

however complex, are of much value, except to suggest the causes of observed phenomena.

The question of suitability of the machine and its adjuncts for the purpose of the research is fully answered by the remarks of Professor Thompson, and I can only add that the problem proved so very complex and difficult to attack that any simplification which appeared possible was adopted, and even then the research occupied two years, but if two more years had been available, I am quite sure that much interesting and instructive information would have been gathered by experiment on the lines suggested by several speakers.

COMMUNICATION.

THE EXAMINATION OF WATER BY ELECTRICAL METHODS.

By W. POLLARD DIGBY, Associate Member.

(*Received April* 14, 1910.

That water in its varying degrees of impurity is anything but a medium of constant value comes within the experience of all engineers, and hence frequent resort is made by the engineer to the analytical chemist for advice and assistance. However, this is not always done as often as might be desired, and a variation in the nature of a supply may take place with no visible change in the appearance of the water, but yet with such changes in the constituents as would render the water quite unsuitable for boiler feed purposes. A case of this nature vouched for by a consulting chemist was recently mentioned to the author. The author's object in the present paper is to point out the value of simple tests made *in situ* as safeguarding the owners of boilers from such happenings, and as determining when the analytical chemist should be employed. These tests are not intended in any degree to supersede the analyst, but may serve to determine when detailed analyses are necessary by indicating changes in the impurities in the water. The method resolves itself into a determination of the conductivity of the liquid at any predetermined temperature and a comparison of such determinations with the known values of analysed samples. Any marked variation from the normal should be followed by a further analytical examination.

That the presence of small traces of impurities in distilled water occasions great changes in the specific resistance is a well-known fact in physics. Measurements of specific resistance have hitherto demanded careful laboratory determinations. The method most widely known, viz., that of Kohlrausch, depends upon the employment of the Wheatstone Bridge, with an alternating current and a telephone receiver in place of the galvanometer used in ordinary resistance measurements. This method, while indubitably one of precision in the hands of those highly trained, permits of varied results from different experimenters dealing with identical solutions, the reason for which is that the human ear is not a standard piece of apparatus for defining the precise degree of minimum sound. Another laboratory method provides for carrying the liquid to be measured in a glass tube forming a secondary short-circuited coil of a static transformer. While this device is visual rather than aural, the delicate instruments necessary, together with the calculations required, relegate this most ingenious

apparatus to the physical laboratory. For determinations of the conductivity of liquids or electrolytes the apparatus to be employed should not necessarily involve the use of alternating currents, and a measuring apparatus fitted with a scale should indicate conductivity in reciprocal ohms or reciprocal megohms as a function of the current furnished by the generator. On the electrochemical side the effect of polarisation has to be limited. This can be effected by circulating the liquid under examination past the electrodes at such a rate as to wash away any adherent film of hydrogen bubbles.

An apparatus embodying these features has been devised by Mr. C. W. V. Biggs and the author, and has been used on all the experiments and tests described in this paper. The original type consists of a straight glass tube so constructed as to hold the equivalent of a body of liquid 10 cm. in length and 1 sq. cm. in sectional area, the liquid being contained between platinum electrodes attached to plugs of ebonite fixed in cups which form enlargements of the ends of the tube. The electrodes are suitably connected to terminals in the ebonite ends, and are capable of being adjusted. The liquid to be tested is introduced into the main tube through a small tubulure rising at an angle from the middle of the upper part; and when tested is run off through a small tube furnished with a tap, attached to the middle of the lower part. At each end of the upper surface of the body tube a vent tube is attached, inclining to the middle of the main tube, and the two unite at a height of about 2½ cm. above it, with a short vertical outlet. The arrangement is shown in Fig. 1.

Manifestly such a piece of apparatus is hardly suitable for use outside the laboratory. The form for practical work consists of a glass U-tube, to which is attached at the lowest point of the bend the tube brought from the filling funnel, whilst the outlet, controlled by a glass tap, is joined to the inlet at its lowest point. Near the extremities of the limbs of the main tube overflow ways are sealed on, and terminate in indiarubber tubes grouped with the lower outlet. The form and arrangement of the electrodes are especially designed to minimise the disturbing effects of polarisation and other difficulties inseparable from the original type of tube. The electrodes are open cylinders of platinum, about 9 mm. in diameter and 3 mm. in height, connected by three equidistant platinum wires to stout brass glass-covered rods passing through the brass covers which are connected to the terminals. The dimensions of tube and electrodes are such that the equivalent of a body of liquid having a length of 10 cm. and a sectional area of 1 sq. cm. is obtained. The apparatus is mounted on a strong wooden support carrying a thermometer, and the whole is contained in a lock-up portable case (Fig. 2).

The most convenient instrument for measuring the conductance is the "conductance meter" made for use with the tube by a well-known firm which the author has entrusted with the manufacture of the apparatus. It resembles the familiar "megger," but is furnished with a scale graduated in reciprocal megohms and ohms, and with a tube of

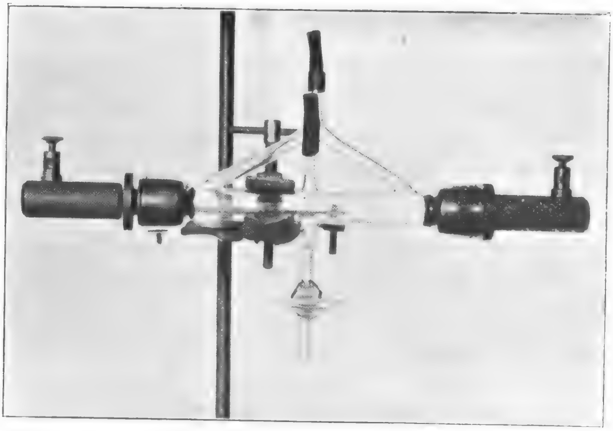


FIG. 1.

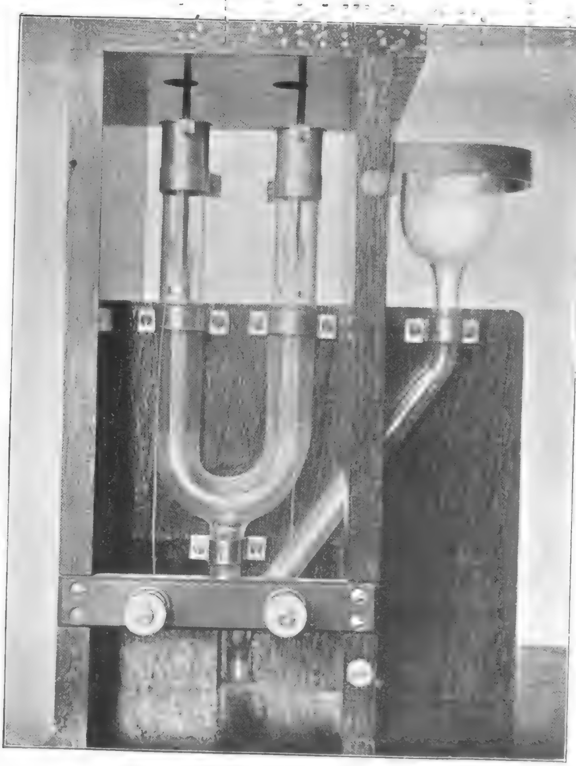


FIG. 2.

sectional area one-tenth the length it gives readings of one-tenth of the specific conductivity—equivalent to the reciprocal of ten times the specific resistance. Correction for variation of temperature for water containing less than 1 per cent. of dissolved salts may be made with sufficient accuracy by taking the coefficient as 2·19 per cent. per 1° C., as referred to 20° C.; but above 38° C. such correction is not reliable owing to complications arising from disengagement of small quantities of dissolved gases, and also from physico-chemical action not within the scope of this paper.

At the outset the author experienced considerable difficulty in determining standards for comparison. Distilled water, obtained either

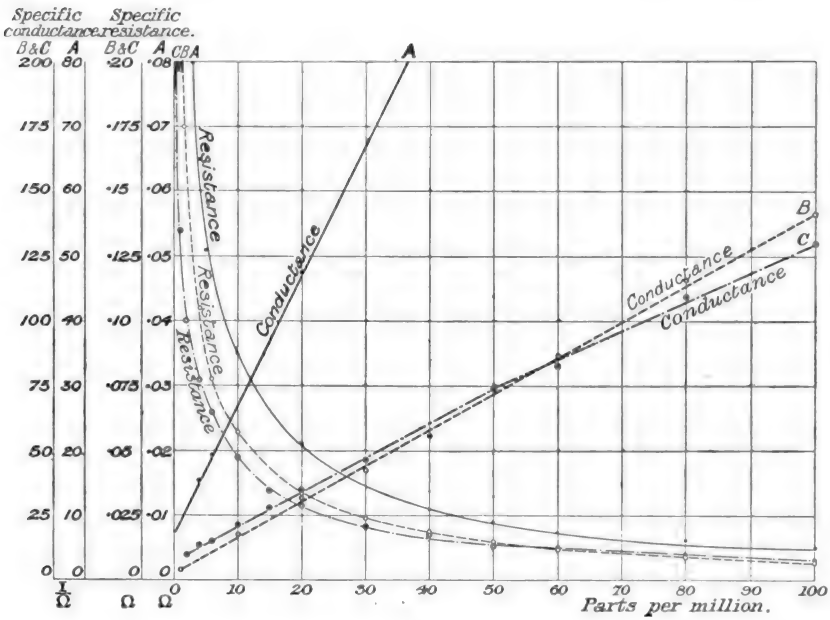


FIG. 3.

from the laboratory of the analytical chemist or from the shop of the pharmaceutical chemist, cannot be regarded as a standard product. Absolutely pure distilled water has probably never been obtained. The best that the author has heard of was a special sample prepared by Kohlrausch, which had a value of 0·043 reciprocal megohm at 18° C. This was prepared by distillation *in vacuo*, and collected in an especial glass cell which had been kept for ten years full of distilled water. Of samples passing through the author's hands, good distilled water has varied in its specific conductivity from 4·0 to 1·362 reciprocal megohms for laboratory distilled water, and for distilled water from surface condensers the best has been 3·3 reciprocal megohms. As a general standard of comparison, good distilled water might possibly be

defined as possessing a specific conductivity of 3·3 reciprocal megohms or a specific resistance of 300,000 ohms at about 20° C., this value representing an approximate average value of the output of the Liebig condensers in the laboratory of one of the author's friends, and also representing the best practice from central station surface condensers that has come under the author's notice.

As has already been pointed out, all books on physics refer to the effect of minute traces of impurities as greatly increasing the conductivity of distilled water. For instance, in the tenth edition of Ganot's "Physics" occurs the statement, "Standing in the air for five hours doubles it; the addition of a millionth part of sulphuric acid—

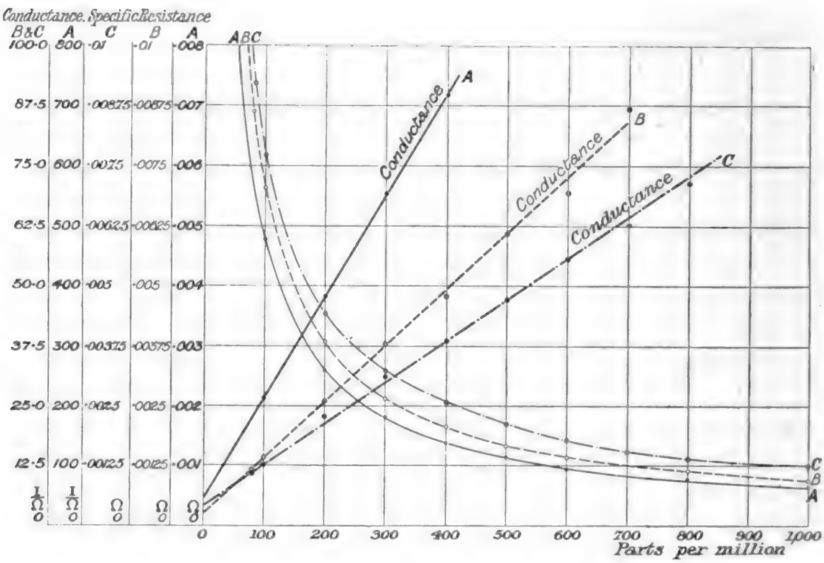


FIG. 4.

that is, a drop in about 17 gallons—increases the conductivity tenfold." The author has noticed that shaking 30 c.c. of good distilled water in a *clean* 50-c.c. stoppered flask for 30 seconds has resulted in doubling the conductivity, probably owing to the absorption of impurities from the imprisoned air with which the agitated water had come in contact. Minute traces of foreign matter having such a great influence on the conductivity of distilled water, the author has carried out a number of investigations upon impurities found in ordinary waters, taking in each case distilled water and salts nominally pure. Some typical results are given in Figs. 3 and 4, which relate to sodium chloride, sodium carbonate and to calcium sulphate. One point must be emphasised by the author at this juncture, and that is that the conductivity tube does not discriminate between different impurities. For instance,

the curves for sodium chloride and calcium sulphate which are superimposed in Figs. 3 and 4 show how similar is the effect of these substances when added to distilled water. All that this or any other method of conductivity determination can do is to indicate variations in the amount of impurities present in a liquid.

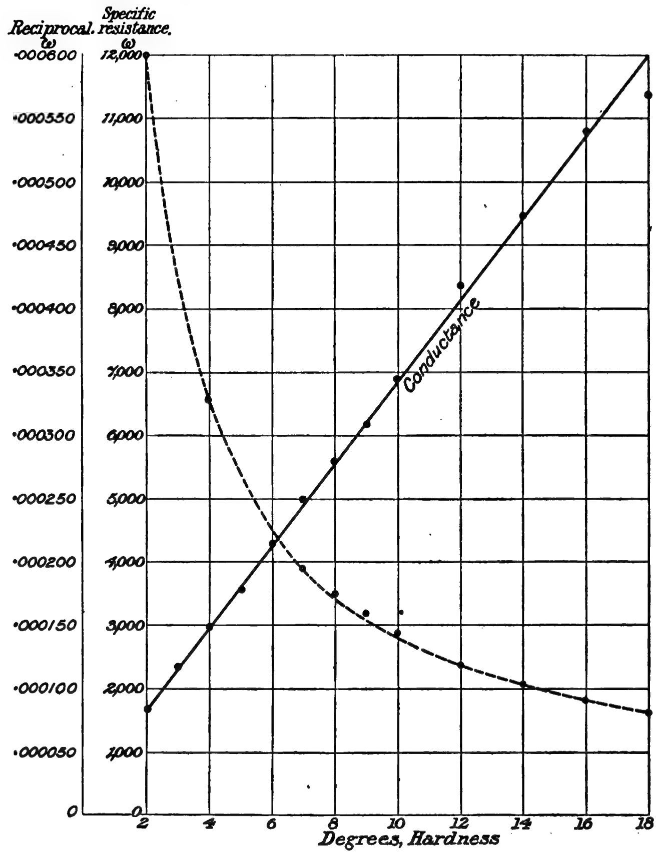


FIG. 5.

Feed Water.—For feed water for boiler purposes such indications are not without value; as an example, Fig. 5 shows the relation between degrees of hardness and conductivity of water when that hardness is due solely to calcium carbonate. From what has been said it is apparent that conductivity tests permit not only the determination of the value of that hypothetically pure liquid, laboratory distilled water, but also the checking of the operation of evaporators for make-up purposes at sea, or for the supply of distilled water for hydraulic gun mountings, and further provide a check on the operation of surface condensers in all places.

Condenser Tightness and Priming.—Given a boiler free from priming, a single conductivity measurement of the water passing from the condenser to the hot well will indicate the tightness of the condenser tubes. It will be urged that any impurities indicated may after all be due to boiler priming. Any doubts upon this score can be readily settled. All that is necessary is to take, say, four or five samples (after running long enough to wash out possible impurities from the steam ways), one with the engine or engines turning round light, and other samples at stated points upon an increasing load. Then if the conductivity is high in the first reading, being anywhere well in excess of

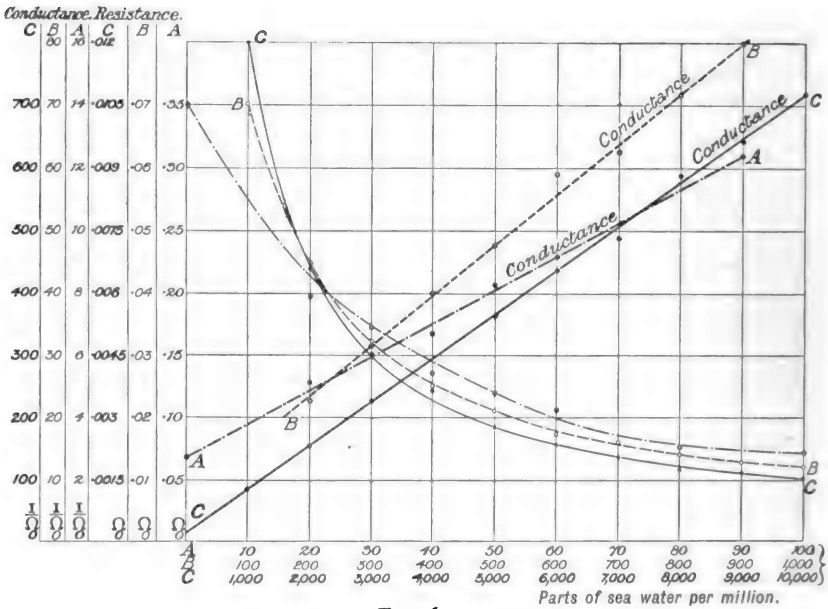


FIG. 6.

a specific conductivity of 3·0 reciprocal megohms, it is obvious that the condenser is at fault, and succeeding readings should confirm this by indicating a lower specific conductivity. If the approximate rate of flow is known at any moment, together with the value of the circulating water, a reference to standard curves will give the percentage of leakage at that moment. Two sets of standard reference curves (Figs. 6 and 7) are appended, one for sea water for circulation (from the North Sea near Sunderland), and one for circulating water having the conductivity of London tap water. It is apparent that a surface condenser may leak slightly for a considerable time. Leaking of tubes obviously impairs the value of the surface condenser as the provider of good feed water, owing to the addition of dissolved solids

in small but cumulative doses to the water in the boiler. This should be checked long before the use of a salinometer becomes possible and before the foaming of the water in the boiler gives rise to priming. Hydraulic pressure tests involving the opening out of the condenser are only permissible when good reason arises for such an overhaul. Conductivity determinations, while indicating when such overhauling is necessary, may save unnecessary examinations. If, on the other hand, the conductivity of the hot-well water, initially low, rises as the load on an engine increases, the only possible deduction is that the boiler is priming. Into the causes of boiler priming such as design, rate of evaporation, height in gauge-glass, or nature of the water

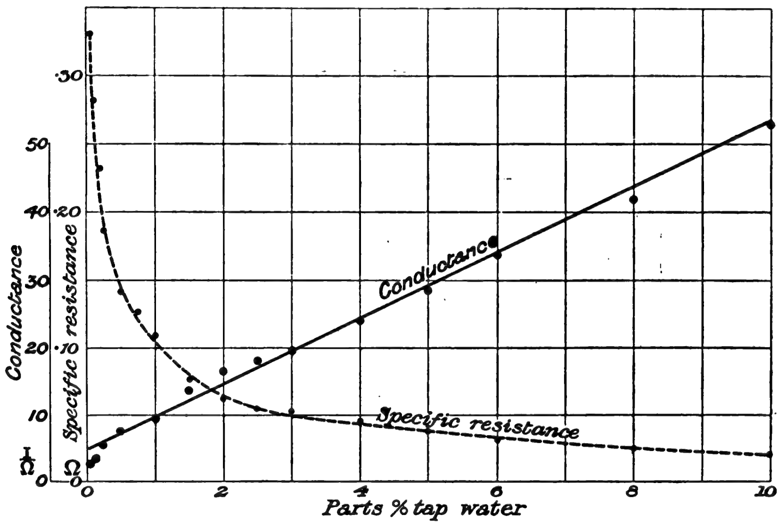


FIG. 7.

within the boiler, it is not within the author's province to deal at this juncture, as the purport of this paper is to describe an exact method of ascertaining the amount of priming taking place. Neither is it within the author's sphere to criticise sampling calorimeters, except, perhaps, to allude to the notorious fact that upon the position of the sampling pipe depends the result of the test, which may be unduly good or unfairly bad. A conductivity determination which embraces the whole of the steam entering the condenser and which does not recognise condensation water due to the radiation of heat from the steam pipes is a better guide as to presence or absence of priming.

The grade of the water within boilers is subject to wide variation. The author has found the specific conductivity of water in boilers to vary from 11·1 reciprocal megohms to more than 90,000 reciprocal

megohms. It therefore becomes necessary for each test for boiler priming to plot a special curve giving the conductivity of various portions of the water actually in the boiler mixed with standard distilled water. Fig. 7 is a special curve showing the conductivity of varying proportions of West London tap water and distilled water.

Tests have been carried out by the author and his staff on several typical installations of boilers. In each case, in addition to an initial checking of the tightness of the condenser, and the determining of the value of the water in the boiler, the following readings were obtained:

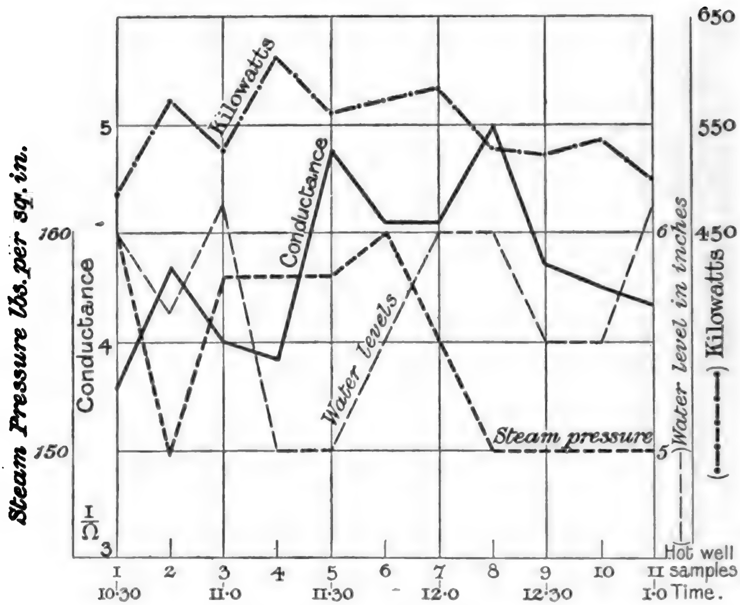


FIG. 8.

(*a*) Height of water in gauge-glass; (*b*) evaporation during period; (*c*) load on station in kilowatts; (*d*) conductivity of sample obtained; (*e*) percentage of priming deduced from (*d*). Inasmuch as this is the first occasion upon which a series of priming tests have been made upon such an exhaustive scale as was employed, and as the method involved permitted of an exactitude of measurement of priming not hitherto available, the author ventures to submit detailed results of certain of these tests.

From April 25th to September 19, 1908, seven tests were taken under varying conditions. The first was on a Stirling boiler at the Shoreditch power station with a load of from 452 to 616 k.w., an hourly evaporation of about 15,000 lbs., and pressure ranging from 150 to 160 lbs. The heating surface was 3,250 sq. ft., and the height of water

in the gauge-glass was from 5 to 6⅛ in. As was the case in all the other tests, hot-well samples were taken every quarter of an hour, whilst an average sample of the boiler water was secured by a slow uninterrupted trickle from the gauge-cock. The duration of this test was curtailed by the breakdown of the mechanical stoker; but the variation in specific conductance of the hot-well samples is very small, the minimum being 3·75 reciprocal megohms and the maximum 5·0 reciprocal megohms. The boiler water was unusually free from saline matter. Its specific conductance, which was 42·5 reciprocal megohms at 13° C. indicates that it contained only from 25 to 30

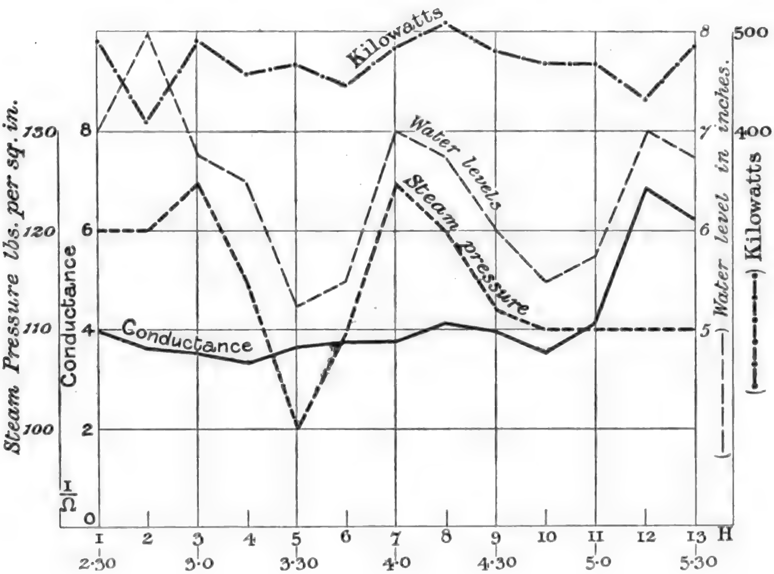


FIG. 9.

parts per million of dissolved solids. Fig. 8 shows the conditions and results of this test.

On May 6th a three hours' test was taken on another Stirling boiler evaporating from 13,250 to 16,235 lbs. of water per hour with a steam pressure of 100 to 125 lbs.; heating surface, 3,250 sq. ft.; height of water in gauge-glass, 5 to 7 in., and a load of 410 to 510 k.w. The boiler water had a specific conductance of 11·1 reciprocal megohms at 19° C., and the hot-well water fluctuated between 3·3 and about 6·8 reciprocal megohms. The boiler water was of an exceptional degree of purity, and contained probably not more than ten parts per million of saline matter.

The details of this test are given in Fig. 9; but the author has not given the curves for percentage of priming in either of the Shoreditch tests on account of the discovery of defects in the tubes used on these

occasions which may have rendered the results inexact. It is manifest, however, from the very low conductance of the hot-well samples, that the priming must have been very slight—probably not greater than 0·1 per cent. in the first test, and not much above this figure in the second test.

The next test, at the Epsom power station on July 15th, was on a dry-back boiler of the Davey-Paxman economic type, and extended over three hours with an hourly evaporation of from 1,048 to 1,185 lbs.

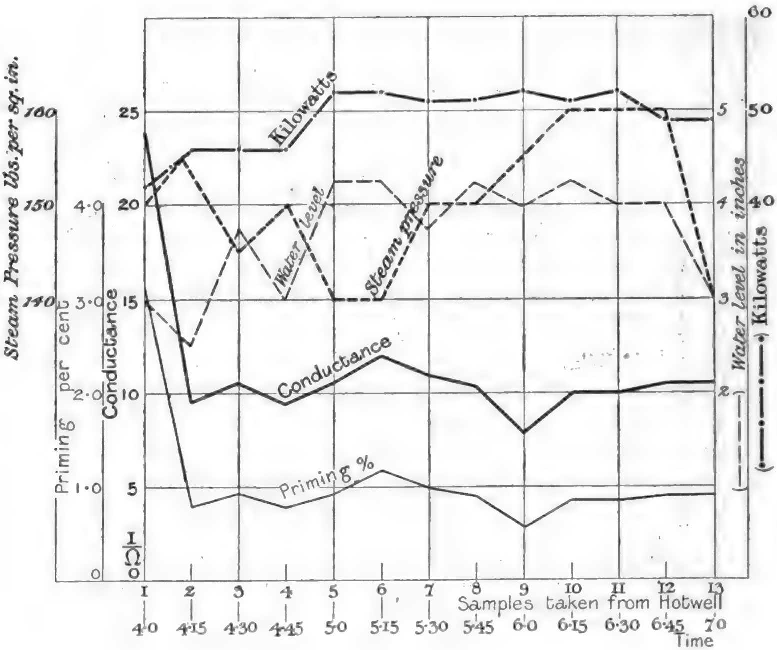


FIG. 10.

of water; a steam pressure of 140 to 160 lbs.; heating surface, 1,180 sq. ft.; height of water in gauge-glass, 3 to 4¼ in., and a load of from 42 to 52 k.w. In this case the boiler water was of a totally different character from that at the Shoreditch station. Its specific conductance was 680 reciprocal megohms at 20° C., representing a proportion of dissolved solids amounting to several thousand parts per million. The hot-well samples varied in specific conductance from 8 to 24·5 reciprocal megohms; but the highest figure was not nearly approached in any other than the first sample taken, and may be ascribed to insufficient washing out of the interior of the pipes before beginning the collection of the samples. The corresponding amounts of priming vary from 0·6 to 3·0 per cent. The curves for this test are given in Fig. 10.

The fourth test was taken on July 24, 1908, at Kelham Island power station, Sheffield, on four Stirling boilers. Nos. 1 and 2 boilers were of the marine type, and Nos. 6, 7, and 9 were five-drum boilers; but No. 9 was doing little or no work, and was merely kept as a stand-by boiler, leaving the four others to run the load. The steam pressure was kept between 160 and 165 lbs., with an hourly evaporation of from 50,184 to 58,423 lbs. of water at 100° C., and a load of 390 to 500 k.w. The combined heating surfaces of Nos. 1 and 2 marine type boilers were 10,640 sq. ft., and the combined heating surfaces of Nos. 6 and 7 boilers were 6,900 sq. ft. No. 9 boiler heating surface was 3,610 sq. ft. The water-levels varied from 2½ to 6½ in. The boiler water from Nos. 1 and 2 boilers had a specific

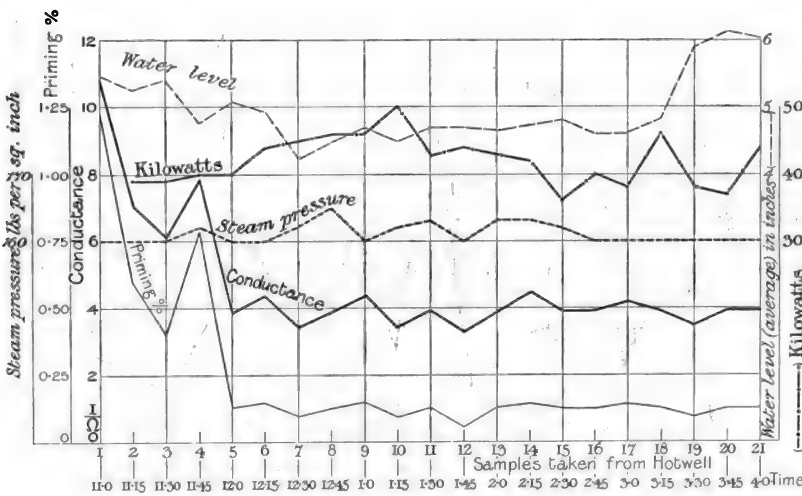


FIG. 11.

conductance of 66 reciprocal megohms, and that from Nos. 6 and 7 of 870 reciprocal megohms at 26·5° C.; whilst the hot-well samples, taken from 11 a.m. to 4 p.m. every quarter of an hour, varied from 3.32 to 10·77 reciprocal megohms. The corresponding percentages of priming range from 0·06 to 1·24, as shown in Fig. 11. As was the case at Epsom, the highest figure was obtained from the first sample only, and the same remarks apply. It should be noted that after the fourth sample, giving 9 reciprocal megohms, at no time did the conductance exceed 5.

Southend power station was selected for the next test on September 1, 1908, when the samples were collected during four hours. A Babcock and Wilcox boiler, with a heating surface of 2,900 sq. ft., and a water-level of 4½ to 6¾ in., was evaporating from 9,526 to 10,940 lbs. of water per hour at pressures of 140 to 160 lbs. with a load which varied considerably. The boiler water was strongly

alkaline, and its specific conductance at 17° C. was approximately 91,240 reciprocal megohms. The hot-well samples had a specific conductance of from 3 to 23 reciprocal megohms at 16° C., indicating priming not exceeding 0·022 per cent. Fig. 12 gives the details of this run.

On September 2nd, also at Southend power station, a four hours' test was begun on a Stirling boiler. After an hour and a half it was found necessary to join up a Babcock and Wilcox boiler, so that this run cannot be regarded, as was intended, as a comparative test, but it shows very interesting results from the time of joining up the

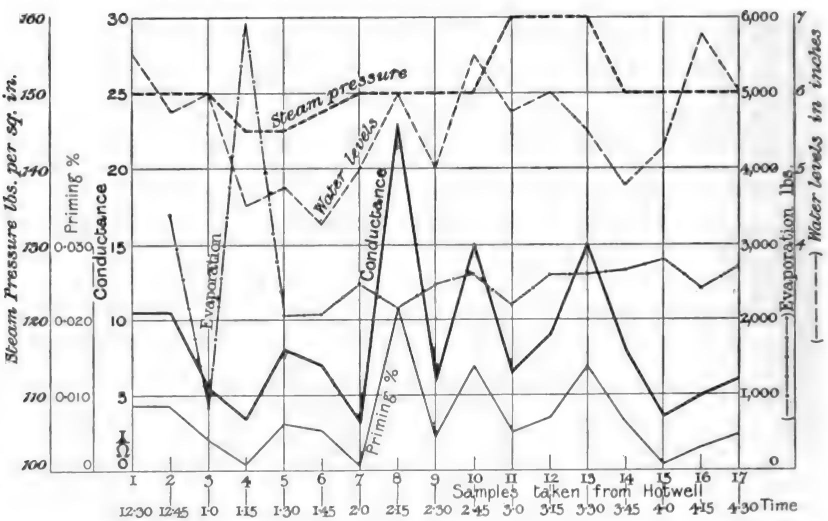


FIG. 12.

boilers until the end of the run. The load was subject to rapid and extensive fluctuations, with an evaporation of from 7,996 to 11,709 lbs. at a pressure of 120 to 150 lbs. The heating surface was 2,910 sq. ft., and the water-level was from 1½ to 5 in. in the gauge-glass. The specific conductance of the boiler water was 6,925 reciprocal megohms at 17° C. Neglecting the eighth hot-well sample, which was taken just after the auxiliary boiler was connected up, and contained much suspended solid matter, the hot-well specific conductances varied from 4·5 to 9·5 reciprocal megohms before the eighth sample, and from 9 to 85 reciprocal megohms thereafter, the corresponding degrees of priming being from 0·042 to 0·1 per cent. for the Stirling boiler and from about 0·1 per cent. to 1·0 per cent. for the two boilers working together. The high conductance of the hot-well water when both boilers were joined up was probably due to the washing out of dirty steamways, for all the samples giving high

readings were contaminated with more or less of earthy suspended matter. The curves relating to this run are given in Fig. 13.

The seventh and final test of this series was taken at Southend power station on September 9, 1908, on two Davey-Paxman economic boilers, having a combined heating surface of 2,360 sq. ft., evaporating jointly from 8,736 to 10,524 lbs. of water per hour at a pressure of 145 to 150 lbs. with a very variable load. The water-levels in the gauge-glasses measured from $2\frac{1}{2}$ to 7 in. The boiler water had a specific

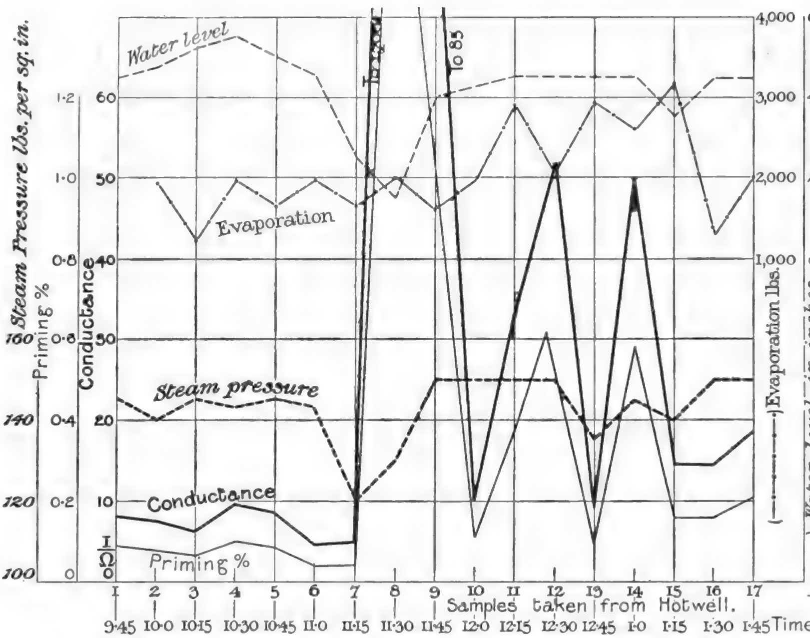


FIG. 13.

conductance of 14,910 reciprocal megohms at 18° C., whilst the hot-well samples, taken during four hours, ranged from 4·0 to 23 reciprocal megohms, and the extent of priming indicated varies from about 0·02 to 0·16 per cent. (Fig. 14).

So far as checking the operation of steam plants by conductivity methods is concerned, their application does not cease with checking the nature of the feed water, or with ascertaining condenser tightness, or even with defining boiler priming. A film of oil is more to be dreaded than scale-forming impurities in the management of boilers. This obvious truism is cited, not because the conductivity tube described lends itself to defining the quantity of oil present, but because an oil eliminator in one form or another is a necessary adjunct in all electricity supply stations containing reciprocating sets. In regard to their efficiency as oil eliminators the author has no

criticism to make. But, apart from this, their careless operation in a manner other than that designed by the makers may involve the substitution of a less evil for a greater one. The author has good reason to believe that in certain cases an excess of chemicals is added beyond that required for the elimination of the oil. This in cumulative small doses can only result in the increasing impurity of the boiler water through its enrichment with a substance which by common consent is regarded as a source of priming.

A last point may be mentioned. Where hard waters containing an excessive quantity of calcium and magnesium carbonates are softened by the Clark process, the conductivity tube and conductance

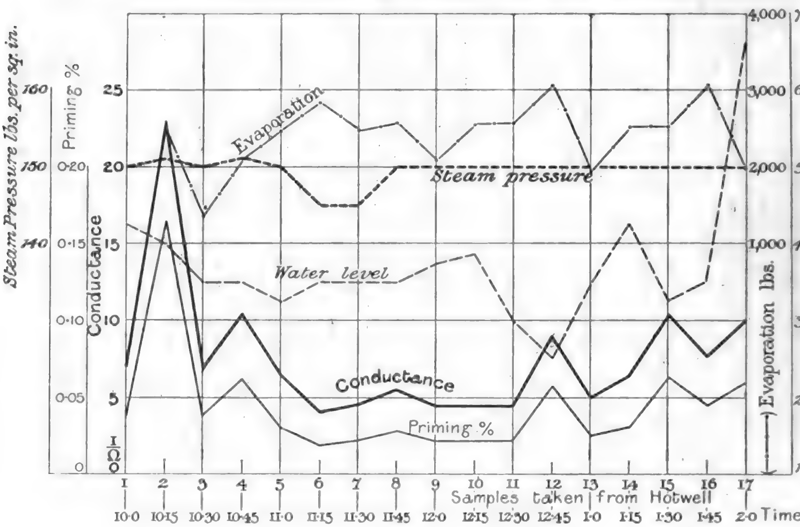


FIG. 14.

meter can be used as a substitute for the standard soap test in defining how far the process of softening has been carried. As an example, the following test and Fig. illustrate the changes accompanying the treatment of West London tap water by the Clark process. Clark's process of softening hard water consists in the addition of calcic hydroxide in the form of a solution or a "cream" of slaked lime, which combines with the carbon dioxide by which calcic carbonate is held in solution in ordinary water, thus forming more carbonate which is precipitated with that originally existing in solution in the water. Calcic hydroxide is soluble in distilled water, at 15° C., to the extent of 119 grains per gallon, and 74 grains will precipitate 100 grains of calcic carbonate from hard water:—

$$\underset{\substack{162 \\ (=100\,CaCO_3)}}{CaH_2 2CO_3} + \underset{74}{Ca2HO} = \underset{200}{2CaCO_3} + \underset{36}{2H_2O}$$

In these tests the hardness of the water as drawn from the tap was 14·5° on Wanklyn's scale, in which the amount of calcic carbonate or equivalent salts is expressed in grains per gallon by the degree of hardness minus 1—*i.e.*, these samples contained 13·5 grains per gallon of dissolved calcic carbonate and equivalent solids having a similar "hardening" effect. Successive samples from the same source were treated with increasing quantities of slaked lime until no further reduction of the hardness resulted; and the readings of the conductance meter agreed closely with the determinations of the hardness. In Fig. 15 the point at which the hardness is given as 4·9° and the conductance 16·3 reciprocal megohms is

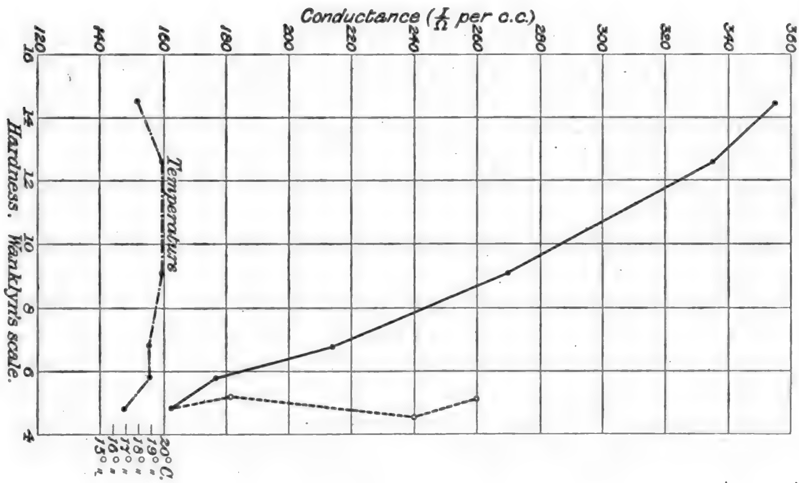


FIG. 15.

approximately the indication of the amount of "permanent hardness" due to salts such as calcic and magnesic sulphates not thrown out of solution by lime, equivalent to about 3·9 grains per gallon of calcic carbonate. The addition of lime was now further continued, and there being no more carbonate with which it could react, it remained in solution, and the conductance readings rose successively to 18·2, 24, and 26. Thus the conductance tube may serve not only to ascertain comparative degrees of hardness, but also to ascertain the point at which the addition of lime should be discontinued in the Clark process of softening, as any excess of lime is made apparent by the rise of conductance.

Conclusion.—To express briefly a *resumè* of the matters dealt with in this paper, the author claims that the determination of the electrical conductivity of liquids offers to the engineer:—

(*a*) The knowledge as to when the analyst should be called in to report upon the nature and probable effect of a change in the constitution of a boiler feed water indicated by the conductivity tube and conductance meter.

(*b*) The knowledge as to whether condensers are leaking, and the amount of the leakage, so that the date for overhaul (immediate or remote) can be promptly settled.

(*c*) An exact determination of the amount of priming arising in any type of boiler under any defined conditions of load, water-level, or nature of water in the boiler.

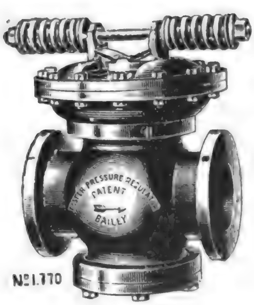
(*d*) The control of oil-eliminating plants, preventing the inadvertent addition of injurious constituents to the boiler feed.

(*e*) The control of water-softening plants.

Further, by actual tests of plants in operation the author has shown, by a method not previously used, the almost entire absence of priming in the boilers mentioned in the tests under the conditions ruling at the respective power stations.

The author does not claim to have discovered the conductivity tube, nor to have discovered any new law relating to the properties of solutions. Hitherto conductivity determinations of liquids have been a matter for the physical laboratory, and Kohlrausch, Fitzgerald, and Whetham have carried out exhaustive researches as to the physical aspects. Perhaps it is not unjust to say that the conductivity tube has been ultilised chiefly as a weapon in the controversies that have been waged over and around a moot point in physics. All that the author can claim to have done is to have described and devised a form of tube for utilisation not only in the physical laboratory, but in the everyday routine of engineering work. In short, the tube described, with its provisions for eliminating polarisation, with its relatively high resistance path between the electrodes, combined with a conductance meter, at once commercialises the research of the laboratory, and affords to the engineer simple, immediate, and at the same time accurate means of control of numerous operations. Those operations which relate to steam-engine work have been amply indicated in this paper.

In conclusion, the author desires to be allowed to express his indebtedness to his colleague, Mr. C. W. V. Biggs, for general assistance upon these researches; to his colleague, Mr. F. E. Pollard, for direct assistance upon the boiler priming and water softening tests; and to his assistants, Messrs. A. C. Huskinson and C. L. Roberts, for routine laboratory work. He is also indebted to his friend, Dr. S. Rideal, for friendly counsel, and to the officials of the central stations mentioned for their permission to take, and assistance in carrying out, the boiler priming tests herein described.



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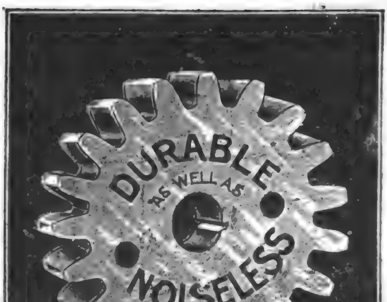

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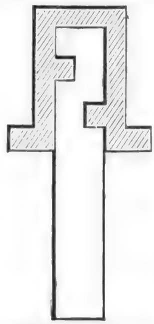

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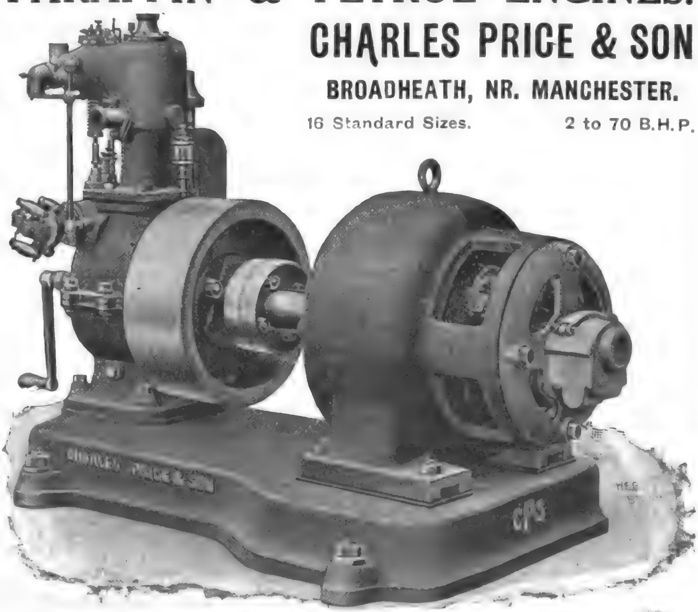

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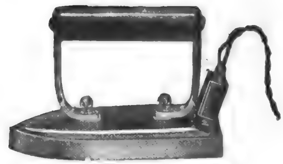

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JOURNAL

OF THE

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Founded 1871. *Incorporated* 1883.

VOL. 45. 1910. No. 204.

Proceedings of the Five Hundred and Eighth Ordinary General Meeting of the Institution of Electrical Engineers, held in the Rooms of the Institution of Civil Engineers, Great George Street, Westminster, S.W., on Thursday evening, April 28, 1910—Mr. S. EVERSHED, Vice-President, in the chair.

The minutes of the Ordinary General Meeting held on Thursday, April 21, 1910, were taken as read, and confirmed.

Messrs. A. P. O'Brien and J. Girdlestone were appointed scrutineers of the ballot for the election of new members, and, at the end of the meeting, the following were declared to have been duly elected :—

ELECTIONS.

As Associate Members.

Lieut. Edward David Carden, R.E.
James Herbert Edwards.
Edward Harriss.
James Raymond Henry.
Raleigh Hills.
George John Hollyer.
Frank Henry Horner.
Robert Hunter.
Edgar S. Hurlbatt.
Adolf William Isenthal.
Henry John Alfred Jones.
Douglas Neill Keith.
Frederick James Launchbury.
Capt. Hugh Percival T. Lefroy, R.E.

As Associate Members (continued).

Bradley T. McCormick.
Frederick Charles Osborne.
William J. Richards.
George William Richardson.
Robert James Roberts.
Gilbert Rosenbusch.
Frederick Peake Sexton.
James Stewart Smyth.
James A. V. Thomson.
George Henry Vaughan.
John Anthony Woods.

As Students.

Singh Anant.
John Henry Asdell.
Daniel Dadsworth Barber.
Harry Edwin Betts.
Alfred Ernest Boon.
Walter Muir Cranston.
Heber Ewart Crowcroft.
Rhys Davies.
George Martin Doubleday.
George Eagar F. Graham.
Frank Saunders Heywood.
Edward Hughes.
William Inglis.
Sydney Norbury Jackson.
George Tenison Levinge.
Robert Edwin Livesley.
John Herbert Lough.
Douglas Wilson McIntyre.
Robert Alfred Mack.
Thomas Francis Phillips.
Edward Aloysius Riordan.
Jayaràm Janàrdan Sàvant.
Percy William Scholefield.
Bertram George Spendiff.
Frank Percival Swann.
John Lindley Thompson.
Mervyn Stanley Vernal.
William Arthur Ward.

The following paper was read and discussed: "Earthed *versus* Insulated Neutrals in Colliery Installations," by W. Wellesley Wood, Associate Member (see p. 559).

The meeting adjourned at 9.45 p.m.

EARTHED *VERSUS* INSULATED NEUTRALS IN COLLIERY INSTALLATIONS.

By W. Wellesley Wood, Associate Member.

(*Paper received from the* Newcastle Local Section, *March* 9, *read in London on April* 28, *and at Newcastle on April* 4, 1910.)

A great deal of attention has recently been attracted to the question whether a 3-phase colliery installation should work with an earthed or insulated neutral, and not only are there a number of supporters of both systems, but also a number of long-standing examples of each at work both on high and medium pressures, and with current taken in some cases from a supply company and in others from their own generating plant. Conditions vary so greatly in collieries and mines that what is suitable and perhaps necessary in one case may be absolutely dangerous in another. The principal advantages of each system are as follows :—

Earthed Neutral.

1 Maximum potential to earth of any phase limited to 58 per cent. of line voltage.
2. Leakage to earth probably results in isolation of the damaged circuit.
3. Leakage tripping devices can be used which switch off the supply when an earth occurs on one phase, reducing danger of shock and explosion.

Insulated Neutral.

1. Danger of shock and explosion is reduced, as contact with earth and one phase does not complete the circuit.
2. An earth on one phase does not cause an interruption of supply, for the same reason.
3. Stress on insulation under normal circumstances is less, and liability to flash to metallic casings considerably less.
4. Only two trip coils instead of three are required to protect each circuit where an automatic switch is installed.

Power taken from a Supply Company.—As the principal consideration is the safe operation of the underground plant, it is only proposed to consider briefly how the question affects generating machinery and transmission lines. Many collieries now take their power from a supply company, and where such an installation is connected without the

intervention of a transformer, advantages 1 and 2 of the insulated system are minimised, as an earth on any part of the supply company's mains (possibly in another colliery) will have the same effect as an earth on the installation, but be beyond its control. Under such circumstances, and particularly where the voltage is high, say 5,000 or over, it is probably better to earth the neutral so that a faulty installation is isolated, and the stress to earth on healthy plants kept permanently at 58 per cent. of the line volts. In a high-tension installation the factor of safety of installation is often small, and the sudden rise of pressure produced by an earth on one part of the system may damage the insulation of another part or cause a flash-over on motors. Where the supply is transformed the colliery circuit is a separately insulated one, and the above does not apply.

Generating Plant.—As far as the generating plant is concerned (where a colliery has its own supply) the earthing or insulating of the

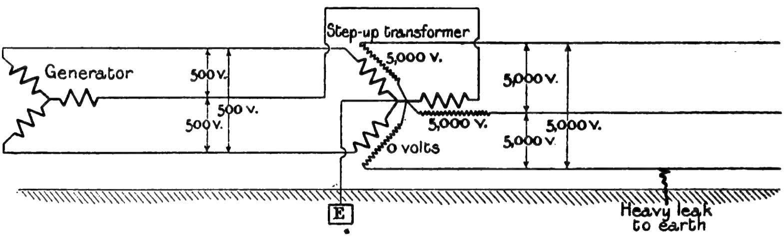

FIG. 1.

1. Transformers connected star to star, neutral earthed, generator neutral unearthed.
2. Earth occurs on one phase and short-circuits it.
3. Voltage on shorted phase falls to zero, on other two rises to full-line volts, increasing stress on insulation of two phases in ratio of 58 to 100.

neutral makes very little difference, as although with alternators in parallel triple-frequency currents may give trouble with an earthed neutral, this can be got over by earthing the neutral of only one generator, or by the introduction of choking coils, and this point was discussed by J. H. Rider in a paper on the London County Council tramways.* The conditions, moreover, under which most colliery stations work are less strenuous than in those of a supply company, where interruption of the service affects a large number of concerns, so that the earthing of one generator at a time would probably work satisfactorily.

Transmission Lines.—As far as transmission is concerned, the question of earthed *versus* insulated neutral is a very open one indeed, especially on voltages under 20,000, and the President of the High Tension Committee of the American Institution of Electrical Engineers in opening the discussion on this subject put his conclusions as follows: "That some plants grounded the neutral, and its engineers considered it safe, and would never think of running in any other way, whilst the engineers of plants which did not ground the neutral would never think of doing such a thing."

* *Journal of the Institution of Electrical Engineers*, vol. 43, p. 235, 1909.

Where the neutral is earthed, it has sometimes been found possible in emergencies to keep up the supply with two lines and an earth return, while with an insulated system the supply can be maintained with an earth on one phase, if the insulation of the system has a sufficient factor of safety to withstand the full-line voltage between any part of it and earth. These points are of more importance on a supply company's system than on the average colliery installation.

Before considering the underground plant it is interesting to note that under certain conditions it is possible to get the full-line voltage to earth in two phases of a system even with the neutral earthed on both high- and low-tension sides of the transformers, if these are connected star to star, and the generator neutral is insulated. This is due to the

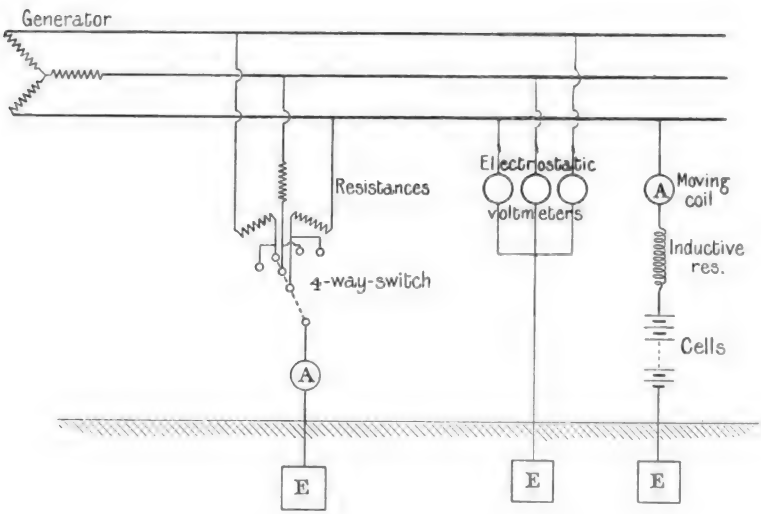

FIG. 2.—Various Types of Leakage Indicators.

instability of the neutral-point under such conditions, and is illustrated in Fig. 1. Very often the first indication of anything wrong is the arcing of the lightning arresters.

Underground Plant.—The chief considerations in the underground plant are safety as regards shock and explosion, reliability and simplicity in working, and cost both of the installation and maintenance of the same.

Danger from Shock.—Although even on a perfectly insulated system of large size, or working at high pressure, it is possible to get a severe shock from the capacity effect alone, and without any actual circuit being completed, there is no doubt that on such a system there is less danger of fatal results from accidental contact with one live phase and earth, and particularly so on medium pressure installations. It must be

noted, however, that very often on these medium-pressure systems the neutral-point is connected to earth through the resistance of the leakage indicator, the connections being as shown on Fig. 2. This resistance is generally designed to pass several hundred milliamperes, which is sufficient to give a fatal shock, and while it is, of course, much safer to get a shock in series with such a resistance which limits the current, this danger can be reduced by using the same electrostatic type of indicator usually supplied for higher voltages, or by the Nalder type of instrument which only passes a few milliamperes. Considered from this point of view there is no doubt that a system with earthed neutral presents greater dangers.

Limitation of Voltage.—With an earthed system the voltage between any point and earth cannot exceed 58 per cent. of the line pressure, but as fatal accidents have occurred with voltages as low as 150, this limiting of the voltage is not of any very great advantage, particularly in a colliery where the conditions are such as to make the men specially susceptible to the effects of electric shock.

Earthing of Metal Casings.—The best protection against the danger of shock from conducting bodies does not lie either in earthing or insulating the neutral, but in properly protecting or enclosing all live parts, and in efficiently earthing to the surrounding ground all motor frames, switch-cases, etc. The earth wire should be large enough safely to carry the load which will blow the fuses of the plant it protects, and it should be frequently tested for continuity. In a dry pit it is often difficult to get a good earth connection, and to meet this difficulty some engineers carry either a separate cable or core for earthing purposes only, but this method may possibly be a source of danger unless the system is also earthed underground, and Fig. 3 has been prepared to illustrate this. For example, on a 3-phase system with an earthed neutral, and an earthplate at the generating supply end, a leak takes place near the motor on one of the outers. This motor is at work in a more or less insulating stratum, so that the resistance from the ground to the earthplate at bank (except through the earth wire) is very high. The motor makes bad contact with the ground on which it stands, and there is a very considerable difference of potential between this ground and the motor. Any one standing on this ground and touching the motor-case will get a possibly fatal shock. If the neutral is insulated it is necessary to have a leak on one of the other phases at bank before the same conditions can apply. It may be thought that this is a rather exaggerated case, but a non-fatal shock on somewhat the same principle as outlined above, and due to variations in the resistance of the strata, occurred recently in a colliery in Scotland, and on measuring the resistance between an earthplate at bank and an earth connection at the bottom of the shaft, this was found to be 100,000 ohms. With regard to this question of earthing, Messrs. J. G. and R. G. Cunliffe * have shown that the resistance of an earthplate is often very considerable. By the kind permission of the authors

* *Journal of the Institution of Electrical Engineers*, vol. 43, p. 449, 1909.

several curves from their paper have been reproduced, and curve I. shows that quite apart from any question of the intervention of non-conducting strata (as mentioned above) the resistance between two plates each $1\frac{1}{2}$ ft. square, and arranged 200 ft. apart, may be about 30 ohms, so that a leakage current of a few amperes would cause a big drop in potential. Another very important point is that nearly 50 per cent. of this drop occurs within 3 ft. of the plates (curve II.). It appears all the more necessary, therefore, in earthing the metallic dead portions of any system to provide several earthplates distributed

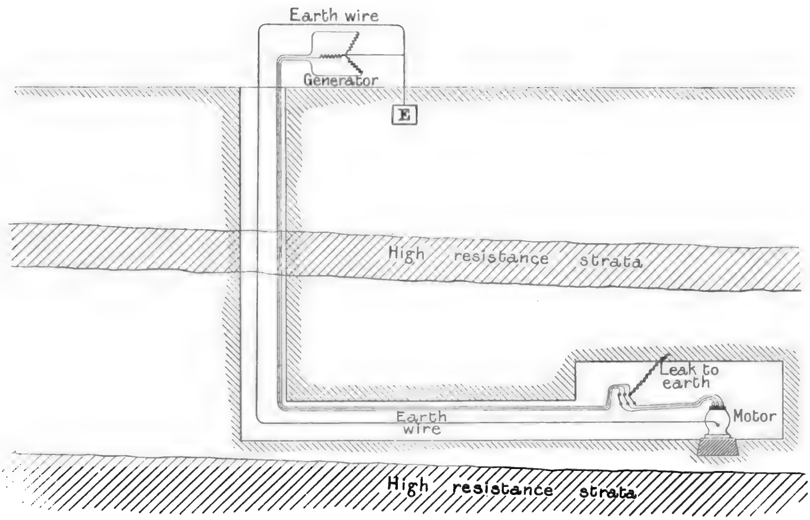

FIG. 3.

1. Motor at work in high-resistance strata, or in motor-room with such strata intervening, both above and below, between earth-plate at bank. No earth-plate underground.
2. Leakage or earth on one phase at same level as motor. Latter on concrete foundations insulated from surrounding ground, and maintained by earth-wire at same potential as earth-plate at bank.
3. Considerable difference of potential between motor and surrounding ground, with possibility of shock due to phase volts.

over the installation. Curve III. shows that there is no great advantage in making each plate more than about 4 sq. ft. in area.

Danger of Faulty Insulation.—There is, however, a possible danger of shock which cannot be guarded against in this way, and that is by coming in contact with faulty insulation, such as an unarmoured damaged cable. With an earthed system shock as before is certain, with an insulated system it is likely to be less severe. Where cables are armoured or enclosed in a metallic covering this danger cannot occur *as long as the armouring or cover are efficiently earthed and electrically continuous.* If, however, a careless jointer leaves the armouring disconnected after a hurried repair, or the armouring is eaten away

by bad water, etc., the conditions are now more dangerous than before, as an earth may cause a considerable length of armouring to be alive, any part of which will give a shock. For this reason many colliery engineers object strongly to the use of armoured cables as being likely to produce a false feeling of security.

Danger from Explosion.—It is very doubtful whether many colliery managers would instal electric plant at all in places where there is real and constant danger of inflammable gas or coal dust, as it seems fairly certain from recent experiments that an arc or flash with any moderate amount of power behind it will ignite either gas or coal dust in suspension if present in suitable proportions. With an earthed neutral failure of the insulation of one phase to earth is practically bound to produce such a flash, while with an insulated system an earth on one phase shows on the leakage indicator, and there is, at any rate, a greater chance of isolating the section before any arc occurs.

Reliability of Supply.—It is sometimes desirable to run certain plant even although it may be in a damaged condition. The stoppage of, say, a main haulage gear will disastrously affect the day's output of coal—a matter of very great importance to the colliery manager—and very possibly if the plant can be kept going for a few hours till the end of the shift, the fault can then be remedied without disorganising the working of the pit. In many such cases it may be perfectly safe and advisable to run, and as the majority of failures of colliery plant are leakages to earth, an installation with earthed neutral is likely to give more trouble than an insulated system.

If leakage trips are indiscriminately used, it is probable that unnecessary interruptions from trivial causes may be sufficiently troublesome to prejudice the manager against electricity and lead him to adopt some other motive power.

Leakage Tripping Devices.—Several very interesting devices have been recently put on the market arranged to cut off current as soon as any leakage current exceeding, say, ¼ ampere flows. They are only designed for use on a system with a neutral earthed either directly or through a resistance, and the current at which they operate can be adjusted to different values on different feeders as may be required. It is claimed that by using such switches in connection with armoured cables danger from shock and explosion is largely avoided, and Mr. Wedmore * gave the results of some very useful experiments on cables which tended to show that with such a device and armoured cables it was very unlikely that a fall of the roof could so damage the cable as to cause flashing or arcing externally. Even without the leakage trips and with only the ordinary overload devices it appeared to be generally necessary to subject the cable to "successive blows of a heavy hammer" before flame occasionally issued, and apparently also high-tension supply was safer in this respect than medium pressure. In case a

* *Transactions of the Institution of Mining Engineers*, vol. 38, pp. 416–430, 1910.

cable were actually suddenly severed, it seems hardly possible that a flash of sufficient energy to ignite an explosive mixture could be avoided, whether a leakage trip was installed or not, and particularly if the point of failure was comparatively near generating plant of large capacity. It must be borne in mind, however, that many cables are run in places where there is no danger of explosion or of mechanical injury. It must be also noted that these devices depend absolutely on the continuity of the armouring or earthing being maintained, and if through carelessness or other cause this is not done they afford little protection against explosion and practically none against shock. A motor standing on concrete foundations is on a very good insulator, and if the earth connection is broken or inoperative insufficient current would flow to operate the leakage trip in case of leakage to the motor frame, which would then be raised above earth potential (Fig. 4). We have previously seen that as long as earth connections are kept in good

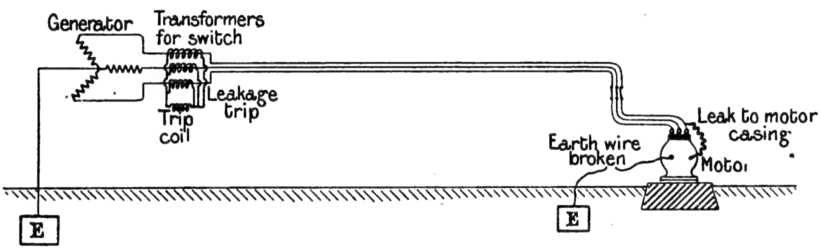

FIG. 4.

1. System with leakage tripping device, and earthed neutral.
2. Earth or leak on motor. Earth wire broken. Motor on concrete foundations, and practically insulated from earth, hence tripping device inoperative.
3. Motor frame at potential of one phase, with possibility of shock to surrounding earth due to phase voltage.

order there is no danger of shock from motor or switch casings or armouring, so that while there are undoubtedly many cases in which a leakage device may be of considerable use there are also many others where it would not justify the increased expenditure and would probably prove rather a nuisance. These devices, moreover, do not protect against shock from live terminals or from contact with a high-resistance leakage.

Simplicity of Installation.—In the author's opinion the simpler the installation can be made the more likely it is to be kept in good working order, and it has generally been found in the past that it is better to rely upon having good men to look after the plant and see that small details such as earthing, etc., are properly attended to than on automatic appliances.

Stress on Insulation.—As long as a system with insulated neutral is in good order the stress on the insulation is 16 per cent. less than on an earthed system, so that under equal conditions its factor of safety is greater. There is no doubt also that much greater clearances and

creeping distances to all metal work must be provided where the neutral is earthed, to give the same factor of safety as on insulated systems. The advantage of the earthed system is that an earth on one phase soon isolates the faulty part, and does not increase the stress on the other parts of the system, while a similar occurrence on an insulated system doubles the stress on the other places and is likely to cause further breakdowns. This point is of greater importance on extra high voltages.

Cost of Installation.—While not necessarily the first consideration, the question of cost in all engineering problems is of very great importance and one that will not be neglected by the colliery manager, whose business it is to get the best possible financial results.

Where automatic oil switches are used, three relays, one in each phase, are needed with an earthed neutral, and only two with an insulated neutral. If many switches are needed, the difference in first cost may be considerable.

The cost of armoured cable is often nearly double that of unarmoured, so that if these are run in places where there is no danger of accidental contact, damage from falls of roof or sets off the line, or of explosion, armouring is an unjustifiable expense.

The cost of maintenance is generally of greater importance than first cost, and it is here that the simplicity of the installation is of primary importance.

Conclusions.—No hard and fast rules can be laid down, and every case should be considered broadly on its own merits, but it certainly seems that generally an insulated neutral is better where permanent plant is at work and the cables are not very liable to mechanical damage. Where portable machines such as coalcutters are used, or where cables are liable to frequent hard usage, it may be worth while to use automatic devices; and in this case, if a separate transformer were used to supply this plant, its neutral could be earthed (and preferably through a resistance) without interfering with the remainder of the system. Such devices, however, will require constant inspection. There is another very important case which has not so far been considered, and that is where small lighting transformers are used. It would seem desirable to limit the secondary pressure of these to 110 volts and connect either the neutral of one side directly to earth. Finally, the author wishes to disclaim any sympathy with the present scare in regard to the use of electricity in mines. It is necessary in a paper of this sort to consider how accidents can and may occur, but the number that actually do occur is extraordinarily small considering the present widespread use of electricity and the insufficient electrical staff employed in many collieries. The average number of deaths caused by the use of electricity in mines appears to be about 1 per cent. of all the accidental deaths in such places, and many of these cases have been due simply to pure accident or carelessness which nothing could have prevented.

Discussion.

Mr. Wilson.

Mr. J. G. Wilson: The keynote of the paper is that each case should be considered on its merits, but there is also, I think, a tendency on the author's part to advocate an insulated neutral, or at any rate to avoid the general practice of earthing the neutral. In fact, in his conclusions, the author says: "It certainly seems that generally an insulated neutral is better where permanent plant is at work and the cables are not very liable to mechanical damage." Those qualifications cut down the conclusion, because in the generality of work in mines portable tools are supplied with electricity underground, and cables underground are as much as any liable to mechanical damage. I would advocate the general practice of earthing the neutral, and would further say that whether the supply to the pit is transformed down from a supply company's system, or is generated locally, all underground cables should be armoured, and the armouring should form a continuous electric connection both to earth and to the neutral-point of the system. To take first the chance of damage from shocks, I question very much the first advantage claimed by the author that the danger of shock is reduced by an insulated neutral. Where the supply is anything like a large one to a scattered district of motors underground, it is in practice impossible to avoid leakages to earth occurring on one phase or another, and even where it is possible it could not be done continuously, and a safety which is available sometimes only and not at all times is not a satisfactory kind of safety to count upon. Moreover, Mr. M. B. Field has pointed out* that even apart from earths on the different phases the tendency of the capacity effect is to keep the neutral-point of the system at or about ground potential, and that insulating is really no safeguard against shocks. He says: "We also see that keeping the neutral-point of an extensive system unearthed is absolutely no safeguard against shock to a human being should he come in contact with one pole. The capacity effect is such as to render the earthed points stable, so that he would receive very nearly the full voltage across the body producing a corresponding current." But a more important question than that of shocks is that of danger from explosion by the ignition of gas or coal dust underground. Assuming that the installation is a good one, and that all the switchgear underground is of the modern enclosed type, perhaps the possibility over which the engineer has least control is the falling of the roofs in the workings on to cables underground. If the cable be a thoroughly well-armoured one it should stand a great deal of this, but if damage should occur to the insulation it is of absolutely the first importance that the supply should be cut off, and this is really the gist of the whole matter. If the neutral-point of the system is unearthed, the supply will not be cut off unless one phase is forced into contact with another; and even then the current has to rise to a value perhaps double that of the capacity of the motors served by the cable, and

* *Journal of the Institution of Electrical Engineers*, vol. 41, p. 215. 1900.

Mr. Wilson.

considerable heating and arcing inside the cable will occur, which may result in exposing an arc outside of it. If, on the other hand, the neutral-point is earthed, the supply can be cut off quite instantaneously, either by a balanced protected system or more simply by a trip coil connected in series with the sheathing of the cable; and this advantage of the instantaneous cut off of the supply is conclusive in favour of earthing the neutral-point of the system. The author has well pointed out the importance of the reliability of the supply, and under that heading he has very rightly suggested that a continual cutting off of the supply by these devices would be very harassing to a colliery manager. But the reliability of supply to a colliery is really most important in the department of winding and fans, both of which are done at bank, and neither of which, if the supply is properly arranged, would be affected by the tripping of an automatic switch in circuit with the underground cables. The temporary cutting off of the supply underground from haulages or even from pumps or coal-cutters, while exceedingly objectionable, should not, I think, be considered where it is a question of actual danger to the mine by explosion. With regard to the question of flashing to the casing of switchgear, I think that is really a question of the design of the switchgear, which is of the highest importance, but really separate from the main issue of the paper. I would advocate the earthing of the neutral in all cases of 3-phase supply to collieries.

Mr. Clothier.

Mr. H. W. CLOTHIER: At the present time the colliery industry has electrical details very much before it, and a decision as to the advisability of earthing the neutral or not is one which is of great importance at the moment. In the author's table of the advantages of the respective systems, it is claimed to be possible with an earthed neutral to isolate a damaged circuit, whereas with an insulated neutral the damaged circuit is not interrupted. To claim both these facts as advantages is contradictory. I think any system which allows a damaged circuit to remain in commission is defective. For instance, with unarmoured cables in mines on insulated neutral systems, if one phase goes down to earth, the potential difference to earth on the other two phases is raised to the full voltage between phases, and there is an imminent danger of the insulation failing in a second place, thus causing "flashing" which is likely to be external to the cables; when considering the question of explosions in mines the risk run thereby is obvious. Consider now the case of an armoured cable with an earthed neutral system; the previous speaker has shown how by the falling of a roof on an armoured cable the chances are that the earthed armouring first makes contact with a conductor, and given a system of instantaneous protection we can release that faulty section before there is any likelihood of flashing external to the cable. I know of instances where there have been falls of roof on cables, and where, owing to the instantaneous isolation, it has been impossible to detect the place where contact was made between the conductor and earth. The illustrations in the paper, I am assured, should not be taken too

Mr. Clothier.

seriously. Fig. 1 shows a very unusual connection, and to my mind would point, if anything, to the necessity of earthing the neutral-point of the generator. Also Fig. 3 is no argument against earthed neutrals. It merely shows the necessity of earthing in several places. I think we cannot have too many earth plates. Suppose that on an insulated neutral system one phase were to go down to the surrounding ground, then owing to the strata being insulated as shown by the author in Fig. 3, the danger exists of the stratum remaining alive without the fault being indicated on the leakage detector at bank. Moreover, it is even possible that a person might get a shock from two different strata separated by a coal seam if one phase were to fail to each stratum. The system of protection shown in Fig. 4 is that devised by Mr. Price. At first sight the figure might be taken as an instance where this system of protection fails, but the figure is incomplete because it does not show the metallic earth return. The figure rather reminds one of the importance of having a sound earth wire. I think the author's description of the size of the earth wire is not a particularly happy one. He suggests it should be large enough to carry the load which would blow the fuses. Such a wire might be a comparatively small one, and really much too small for this purpose. The mechanical strength of an earth wire is a point for consideration.

The cost of the system of leakage protection shown on Fig. 4 is little or nothing more than that of ordinary overload protection. The price comparison of unarmoured and armoured cables as given by the author also requires qualifying. He says that the latter are double the cost of unarmoured cables, but this is not always the case. For small cables the difference in cost may be as much as 40 or 50 per cent., but in larger cables it is only about 20 per cent., allowing for double armouring. With single armouring the difference would be still less. In conclusion, I suggest that (1) there should be a sound metallic and continuous armouring throughout the system, that is from the generators to the load; (2) this armouring should be efficiently earthed; (3) we should then earth the neutral, if only to obtain thereby a better and safer system of automatic protection.

Mr. Patchell.

Mr. W. H. PATCHELL: I would emphasise the great importance of the first half-dozen lines of the paragraph on page 562 referring to the earthing of metal casings. The protection put round the conductor should, in my opinion, wherever possible, be metallic and thoroughly well earthed, and that is much more important than the question of earthing or not earthing the neutral. The earthing should be thoroughly good and sound. A friend told me recently of an unfortunate accident which occurred where a man had, in a case of a damaged armoured cable, bared back the jute, lapped a wire round it, picked up a handy iron casting, lapped the other end of the wire round it, buried it, and went away thinking he had properly earthed the cable, and that there would be no danger. A thing like that brings discredit on the whole profession, because that man was at the colliery list as an electrician. After all, it is useless to have perfect safety appliances fitted unless the men who

Mr. Patchell.

have to look after the plant understand their business. If less money were spent on automatic safety devices, and more money on skilled attendants, I think there would be fewer accidents. We have heard a great deal, perhaps more or less indefinitely, of faults due to falls. It is very hard to trace the effects of a fall in a mine. Mr. Clothier said just now he had examined a case of this kind and could not see where there had been an earth. What the risk is it is almost impossible to tell, but it is something that we must avoid, whether it is 1 in 10,000, or 1 in something less. I fortunately have escaped anything of the sort, which may be more by good luck than anything else, but my friends have been ready to put in good sound work every time. On inquiring of others who are interested in this class of work, I have never yet heard of a fault where there has been a flash due to a fall that could be directly traced to the fall. I do not say such a thing cannot happen, and I think electrical engineers should take precautions to prevent an accident from such an occurrence when it does happen. But what we are to do or how much money is to be spent to insure against the risk is, after all, a commercial proposition. In discussing transmission lines on page 560 the author mentions remarks by the President of the High Tension Committee of the American Institute of Electrical Engineers, but the gentleman to whose conclusions he refers is Mr. Charles Scott, of the Westinghouse Company, who was at one time President of the American Institute of Electrical Engineers. The remarks were in Mr. Scott's contribution to the discussion on Blackwell's paper in connection with the work of the High Tension Committee, and they were made in 1903. Whether the conditions are much altered since then depends also on what earthing we are speaking about. The matter was discussed again in 1907 by the American Institute, and as far as that discussion went, the speakers for some cases practically paired on earthing or non-earthing. The Chicago people said that they absolutely believed in earthing, and that their success was due to earthing. A New York man replied that their success in New York was due to non-earthing. The bulk of the evidence seemed to be in favour of earthing the neutral of a distributive system with star-connected transformers. In the American papers earthing is frequently referred to when it is not a question of earthing the neutral-point but of earthing one phase. In the National Electrical Code which constitutes the American fire insurance rules it is laid down that the transformer secondaries of distribution systems should preferably be grounded, and if there be no convenient place to ground the neutral, one phase may be grounded. Looking at the matter hurriedly one is apt to be a little confused by these two ideas. I think we must look the earthing matter fairly in the face. If the neutral be not earthed, there is a risk of something happening which would not happen if the neutral were earthed. But earthing introduces the chance of another abnormal thing happening, which would not have happened if the neutral had been insulated. So after all every particular case goes on its merits, and the operating and personal conditions must be considered before deciding on this important question.

Mr. W. C. MOUNTAIN: The question whether the neutral should be earthed or not in connection with colliery work is an entirely different problem to the high-tension schemes referred to in Mr. Patchell's remarks. In connection with colliery installations, one has two main objects in view: (1) To ensure, as far as possible, that the lives of the men working underground should be protected by having the safest possible system; (2) that the machinery installed underground should also work with the least possible risk of breakdown. It must be remembered that in colliery installations, whilst motors are occasionally run at a voltage as high as 5,000, the ordinary voltages are either 650, which comes within the limits of medium pressure, or 3,000, which is the maximum allowed under what is at present known as high pressure; and the bulk of the work in collieries will be carried out at a pressure not exceeding 650 volts, except for larger motors in connection with heavy pumping and haulage schemes. As earthing the neutral merely limits the pressure which one would receive in getting a shock to 58 per cent. of the maximum voltage, it is quite clear that, as regards safety to life, nothing can be gained by earthing the neutral even on a voltage of 650, because this would only reduce the voltage of a shock to 375, which would be fatal in most cases. With the pressure of 3,000 volts, of course the certainty of death would be greater still. Dealing with the question of mechanical breakdown, I believe that for all voltages up to the limit of medium pressure, *i.e.* 650, and probably up to voltages of 3,000, there is a distinct advantage in keeping the neutral insulated, *i.e.*, not earthing the neutral, because with a proper system of earth detectors, which can be used with an insulated neutral, it is possible immediately to detect the existence of an earth and to remedy it quickly. I have found, after many years experience both with continuous current and later with 3-phase current, that in consequence of changes of temperature, accumulation of dirt on connections, and the fact that in some cases colliery motors do not receive the same attention as motors which can be more carefully examined in daylight, there is always a great tendency (when they are subjected to a constant pressure between the frame of the machine and the conductors due to earthing the neutral) for creeping to take place, which finally breaks down the insulation. I therefore believe that for practical reasons, except perhaps in installations where the voltage is very high, and where there is a difficulty in getting the same comparative degree of insulation in the slots of the motors and on the windings as on medium pressure work, it is not desirable to earth the neutral. There seems to be a great deal of confusion in the minds of men connected with the collieries as to what earthing really means, and when one speaks of earthing the neutral they are liable to confuse it with earthing the machinery itself. I consider and strongly recommend that anything of a metallic nature which is liable to be touched by any of the attendants, and which contains electricity, such as the motor frame and switchgear frame, should be as permanently and absolutely earthed as possible, but in Mr. Mountain.

Mr. Mountain.

connection with earthing it requires to be made clear as to how these permanent and satisfactory earths can be obtained. There is very great difficulty in many dry mines in obtaining an earth, and under such circumstances, unless one relies upon non-earthing of motor frames and the maintenance of a high perfection of insulation throughout, it becomes necessary to consider the armouring of cables and using the armouring as an earth return. It is also possible to lay in the ground disused haulage ropes which can be permanently earthed to the sump and connected to the frames of the motors and switchgear, and this would form a very efficient arrangement. Of course, a further alternative is to have, in the case of unarmoured cables, an earth shield on the cable itself. I know I am not voicing the opinion of some of the leading colliery men in advocating this system of earth frames in preference to the maintenance of a high degree of insulation, and I was informed quite recently that in a prominent colliery in the Midlands where they have had fifteen coal-cutters at work on a totally unarmoured system, and the cutters have been running for twelve years, they have never had an accident of any kind. At one time they suffered from breakdowns of the motor coils and armatures, due to intermittent leakages, but now that they had taken precautions to ensure that any earth which might appear was immediately rectified, the coal-cutters had run almost without breakdown, and they cut as much as 15,000 tons of coal with one machine without taking out the armature or making any repairs. Personally, I believe in the use of armoured cables for colliery work, at any rate where there is any liability of accident due to a fall of the roof, but there are undoubtedly many positions in a colliery, such as in travelling roads and in other places where the roof is well supported, where it is not necessary to use armouring for mechanical protection, and under such circumstances I think it is rather hard to insist upon the use of armouring if it is merely for the purpose of being able to use a protective device, such as the Merz-Price. There is no doubt, however, that where there is any risk of the roof falling and the cables becoming damaged armouring affords a very great mechanical protection, and I consider that generally for colliery work armouring is to be recommended in all installations where the voltage exceeds 650. It is only fair to state that in all my twenty-two years' experience (during which I have installed a very large amount of cable underground), I have never known of the severance of an armoured cable through a fall of roof, and the experiments which were conducted in connection with the previous inquiry into the use of electricity in mines show how difficult it is seriously to damage or to cut a heavily armoured cable. Assuming that armouring is adopted, of course it enables a protective device to be used, and, whilst I do not for a single moment wish to depreciate the advantages of such devices when applied in suitable places, I do not think there are very many positions in an ordinary colliery installation where they are required. To my mind the use of an apparatus of this kind, which is automatic in its action, gives an altogether false sense of

security, and every one knows if one has to depend upon automatic gear such gear has to be very constantly tested and tried to see that it is in working order, and very often when required to work it is found to fail, therefore I consider it is far better to rely upon thoroughly sound mechanical work, constant supervision, and the use of proper earth detectors. To sum up the position finally, while I generally agree with the remarks as to the desirability of earthing the neutral in connection with high-tension central station schemes, I still feel that for colliery work, knowing all the difficulties which exist, a system with unearthed neutral carried out in a sound mechanical manner is to be preferred. Mr. Mountain.

Mr. J. F. C. SNELL: Mr. Mountain has left me at least unconvinced on this question of the earthing of the neutral of 3-phase systems, and although I would bow to his very long experience in collieries, I think the matter he mentioned, namely, the slight creeping and leakage on motors which will set up a potential point of weakness, points to the necessity for apparatus which shall cut out at once such a point of weakness from the system. Mr. Patchell rather digressed in dealing with the system of earthing of transmission lines. We are dealing here with the earthing of neutrals applied to colliery installations, and I am bound to say that, after the very careful investigation which Mr. Patchell and I and a few others had to make on behalf of this Institution in connection with the new Coal Mines Regulations Act, I have felt it is imperative that the neutrals of 3-phase systems should be earthed. Nor does that interfere in any way, to my mind, with the complete simplicity of the system. If a complete system of armouring be coupled with it, it seems to me they will produce a thoroughly good distribution system, one which protects thoroughly the employees from danger of shock, and what is much more important, which minimises the danger of risk of explosion, either of gas or of coal dust. But the cables must be completely armoured, and I would suggest that all the joints ought to be thoroughly bonded and that the frames of fixed machines should be bonded to the armour as well, so that through the whole of the distribution system there would be a completely armoured and protected system providing a stronger cable in case of falls and practically eliminating the earthing troubles, and, in short, affording apparently complete protection against the many dangers which occasionally arise in certain mines. But, of course, it will be necessary to protect the armouring of the cable against corrosive waters. That is a question of design on the part of the cable manufacturers. I was looking up the other day some of the notes in the *Journal of the American Institute*, and I saw there that armoured cables are protected by jute and what they call asphalt. I suppose the following sort of thing does not occur in our English collieries, but one of the objections which one of the speakers had to the protection of the armoured cables by jute and asphalt was the fact that "the miners had a reprehensible habit of removing the jute from the armoured cables and using it for kindling fires." Of course, we do not allow Mr. Snell.

Mr. Snell. fires in the collieries in this country, but it is done in America. Incidentally the same reprehensible persons used "to steal the oil from the transformer cases in order to relight their lamps." · The author goes on to say that armouring is an unjustifiable expense when certain things happen, such as no danger of accidental contact, or damage from falls of roof, or sets off the lines, or an explosion. It seems to me that in those four things are comprised practically all the dangers that exist in ordinary mines, and as I think one or other of them is always present in collieries it would seem that armouring is justifiable and is absolutely necessary. I think, too, armouring should be made compulsory in collieries, because if it be done only here and there the result is a patchy system. If a thoroughly armoured system be looked upon as the standard system of distribution in collieries, I believe it will go a long way to meet the present adverse criticism which is offered by some of the colliery officials in the matter of the electrification of collieries. The author said that "the cost of maintenance is of greater importance than the first cost." I think this is a question in which the first cost is really quite immaterial. If the first cost will give a system which is immune from the dangers which occasionally arise in collieries and gives a greater feeling of security to the electrification of collieries, then I think it would do the whole electrical industry a great deal of good. It would bring about a feeling of security amongst the colliery people, and it will redound in credit to electrical engineers. I think the earthing of the neutral-point of the 3-phase system, coupled with complete armouring, represents the safest, the simplest, and also the best method to adopt for this particular class of work.

Mr. Wedmore. Mr. E. B. WEDMORE: I do not quite agree with the view taken by the author with regard to the statistics at the end of his paper. For those statistics to be of any value I think we ought to exclude all cases where there is no risk from electricity, and if that were done the percentage would stand at a higher figure. It seems to me it lies with us to reduce that figure. I have had occasion to examine in considerable detail the statistics of fatal accidents given in the published reports, and the conclusion I arrived at was that, whilst it is true that in many cases pure chance or carelessness is responsible for them, yet in the majority of cases such accidents could have been avoided by the employment of a system such as Mr. Wilson and others have advocated this evening. I do not think we can look with equanimity on the regular list that is published, which spells hard calamity falling on too many homes in this country from year to year. Referring now to the general details of the paper, the arguments which Mr. Wood gives against earthing the mid-point fail in many cases, in that they are based on the use of defective systems. Figs. 1, 3, and 4 show systems of connections and methods of distribution which ought never to be employed. I hope it will not be thought that the system shown in Fig. 4, where a leakage device is included, was one of those advocated by me. The author seems to suggest that it is a proper course in

Mr. Wedmore.

collieries employing a system with mid-point insulated to operate the plant with the insulation on one pole broken down. One needs a much stronger argument than love of money to justify that in the large majority of collieries. There are obvious potential elements of serious danger where one pole of the system has gone to earth. For example, at the moment it goes to earth an unusual stress is thrown on the other two poles, and is liable to find the weak points on them and bring about a short circuit, which in a colliery is a very much more serious matter than in a surface installation. It is alleged that there is need for better insulation, better creepage surfaces, and better clearances where the mid-point is earthed. I do not quite understand on what ground that argument is put forward. Surely the cable makers have advocated the use of more insulation on cables where the mid-point of the system is insulated. Again, there is a special risk on high-tension systems with the mid-point insulated in the event of a discharge to earth, because that discharge is apt to be of an intermittent character. It will form an arc, limited by the capacity current of the system, but an arc which has capacity and self-induction in series with it, and which is liable, therefore, to be an explosive or humming arc which will set up high-frequency disturbance and find any weak points there are in the system. The argument with regard to the greater safety of operating with the mid-point earthed seems to be largely based on the suggestion that if it be not earthed the system may go to rack and ruin without having a shut down. I am unable to agree, moreover, that there is greater safety where the mid-point is insulated on an armoured system. It is true that if an individual section of armouring becomes isolated from the rest it may be thought there is a greater safety where the mid-point of the system is insulated, but what happens if two or three sections become isolated, as has been known to occur? Immediately one good earth occurs on the system any of these isolated sections that happen to be leaking to the other pole become alive with full potential to earth. The author indicates, as Mr. Patchell has emphasised, the safeguard that can be obtained by providing a substantial metallic cover to switches, motors, and all such devices. I submit that the logical conclusion is to continue that substantial metallic cover over the whole of the electric plant, and earth it at one or more points. If that is granted then I think there are good arguments for the leakage devices. These have been referred to as unnecessary complications. I think that has arisen partly from a misunderstanding as to the character of the devices which have been advocated. In the ordinary course, if the mid-point of a system is earthed one would employ three current transformers and three trip coils to control the three phases. More often than not some delaying device would also be employed on each of the three phases. In the system which I had the honour of describing before the Mining Institute at Barnsley I pointed out that a positive simplification could be obtained by a modification of the arrangement which gives at the same time a discriminating action against faults to earth. My

Mr. Wedmore. proposition was to transfer one of the usual trip coils into the lead common to the three transformers. For that coil there is no necessity for a time limit device, so that one such device is saved. That coil can then be set to operate instantaneously at a fraction of the normal load current, instead of at two or three times the normal load current with delayed action. If one wishes to carry the sensitiveness further, a relay can be substituted for the trip coil, and that is a very simple addition; but if that addition be made the setting can be reduced to 2 or 3 per cent. of the normal full-load current. The experiments which I had the pleasure of detailing in my paper indicated that if a really sensitive device of that kind were employed for giving protection against faults to earth, a damaged cable could be disconnected with extraordinary rapidity; in fact, in some instances one could switch the supply on to the damaged cable five or more times before the leakage to the armouring developed into a real short circuit capable of affecting the usual overload devices on the system. With reference to the leakage device referred to by Mr. Wilson, consisting in the use of a coil in series with an earthing wire, it seems to me that that arrangement is fundamentally defective, because it introduces resistance and reactance into the return wire, and if that wire be made to carry the leakage current there will necessarily be a heavy drop of potential, and the armouring of the cable or apparatus connected to the remote end becomes alive.

Mr. Sayers. Mr. H. M. SAYERS: I am on the side of the earthed neutral, which on a 3-phase system serves two main purposes. The first is that it ensures a definite distribution of the potential, so that the designer of all the apparatus in use on the circuit knows what he has to deal with. He can distribute his insulation to meet the stresses; he can therefore distribute the insulation which he can afford in the most economical and efficient way. If the designer has to deal with an unearthed neutral, then in order to provide equal safety he must insulate everything for the full potential that can come upon it under any circumstances. This implies either a lower factor of safety or more insulation. I claim that the earthing of the neutral affords a distinct addition of economy and efficiency in the use of insulating material for that reason. The second effect of earthing the neutral is that it provides a constant watch upon the insulation of the whole of the system, every branch of the system. Unless there is such a watch, faults may develop, and remain at comparatively high resistance, and fail to be detected until some unfortunate person puts his hand upon, or brings a tool in contact with a faulty cable. I can say from my own experience that in a hot, wet colliery a 100-volt continuous contact to the hand is more than I can tolerate, and many people are equally sensitive to shock. Certainly 250 volts I should expect to be fatal to nine people out of ten under the conditions of high temperature, wet skin, wet surroundings, and wet boots and clothes. I think that destroys the advantage claimed by the author for the insulated neutral as regards danger of shock. Advantage No. 2 of

Mr Sayers. the earthed neutral, "Leakage to earth probably results in isolation of the damaged circuit," should be put more strongly. It is only a matter of having proper devices to ensure that leakage, as discriminated from overload current, positively ensures the isolation of the damaged circuit. Mr. Wood suggests that what he calls the full-line pressure may be put on to two phases with neutral earthed under the conditions shown in Fig. 1. I challenge that. I say positively that the distribution of the voltage shown on the high-pressure side of the transformer in Fig. 1 is impossible. Further, under the circumstances there depicted, the pressure of the generator drops considerably, and any reasonably efficient overload device or leakage tripping device on the circuit would operate. At all events, the connections are obviously incorrect. I cannot understand under what conditions the first indication of something being wrong in a system with an earthed neutral would be arcing at the lightning arrester. I can quite understand that it might occur with an insulated system. With regard to Fig. 3, the trouble could not occur if there were thoroughly earthed armouring on the cable throughout, and that is the proper precaution to take against such dangers. I am very glad that the unanimous opinion of all those who have joined in the discussion this evening is that a completely armoured system is the proper one for standing work. Mr. Mountain made a distinction between movable and permanent apparatus. For movable machines special precautions may be necessary, but there are such things as flexible armoured cables. [Mr. MOUNTAIN: Yes, but you would not like to use them yet.] I suggest that the author's remedy for the state of things depicted in Fig. 3 of local earth-plates is one which might produce other serious troubles; for instance, if the earth wire to bank parts, or carries a heavy leaking current. There are earthed signal wires in collieries sometimes, and if they bridge a high resistance stratum there may be trouble. I believe deaths from shocks from signal wires have already occurred in collieries, and that is a thing we ought to prevent. The scare, so far as it exists, about the use of electricity in collieries is mainly on account of the electrically ignorant man, who may come in contact with something dangerous, which gives no warning and may hurt him.

Mr. Brazil. Mr. H. BRAZIL: Mr. Wilson has forestalled me in some of the points I was going to raise, and I should like to emphasise his remarks as to the danger of shock from touching any pole of a 3-phase system with the neutral-point insulated, by saying that owing to the capacity of the system, it is not a possibility but a certainty that a severe shock will be experienced. Mr. M. B. Field, in the original communication to which Mr. Wilson has referred,* further points out that although if the system is perfectly balanced and the insulation of the three poles is equal, the neutral-point of the system may be at earth potential, there is no certainty about it. If, therefore, we compare the two systems, it will be seen that with the neutral insulated, it is not safe to touch any of the three poles or the neutral-

* *Journal of the Institution of Electrical Engineers*, vol. 41, p. 200, 1900.

Mr. Brazil.

point, whereas with the neutral earthed, at least one of the four points will be safe to touch. In earthing, also, the question has not been raised whether it is best to earth direct or through a resistance. I am of the opinion that earthing through a resistance is far preferable, as it renders the shock to the system at the time a fault occurs very much less, and yet at the same time limits the rise of pressure due to surges and resonance in just as efficient a manner as with the neutral earthed direct. In the discussion on Mr. Rider's paper, I described an earthing resistance of the carbon powder type which was very suitable for the purpose, in that it allowed a comparatively small current to flow to earth when a fault occurred, but as it became hot reduced in value and allowed just as much current to flow as was required to trip the automatic. The resistance at the time referred to was, more or less, theoretical, but since then one has been made, and is in use on a large 11,000-volt system in the North of England. It consists of 72 fire-clay troughs filled with carbon powder and arranged 9 in series and 8 in parallel. With 6,000 volts—the voltage to earth on above system—across its terminals, the current at the moment of switching on will be 200 amperes (1,200 k.w.), and at the end of 1 minute, if the automatic has not broken circuit, 330 amperes (2,000 k.w.). The great advantage of this resistance is that although the current, and therefore the shock to the system, is comparatively small, it will, if the pressure is maintained across it, allow any current within reason to flow, and the automatics are only called upon to break the current for which they are set, instead of ten times that amount, which might be the case with the neutral earthed direct.

Mr. Wordingham.

Mr. C. H. Wordingham: I was brought up in the school of our President-elect, Mr. Ferranti, who was the pioneer of earthing, as of so many other things. I suppose I have been trained to the idea that earthing affords security, and I am bound to say I see no reason to modify that feeling. The plan of action is deliberately to earth a conductor and know it is earthed, and then if anything else happens it must mean a short. In the case of a 2-wire supply the work is done at maximum stress and the conditions are known to be the worst possible, for when both poles are insulated and one pole goes to earth the stress on the other is suddenly doubled, with breakdown of one or more weak places in consequence. Therefore I strongly endorse everything that has been said as to the safety of earthing. But I also consider direct earthing to be the only effective method. It has always seemed to me a weak point in central station work to earth the middle wire, but to put a resistance in, or cut one in when a fault comes on, it amounts to saying that earthing is done to provide for emergency, and directly the emergency arises a resistance is put in which partly destroys the effect of earthing. I therefore strongly advocate the practice of direct earthing, and not earthing through a resistance. One point which naturally arises is the difficulty of finding an efficient earth. I know that one of the Committees of the Institution has found it difficult to lay down rules on the subject.

Mr. S. Z. de Ferranti: I do not want to offer, at this late hour, any argument as to the desirability of earthing; I simply want to repeat what I have often said before in other circumstances with regard to earthing. I think that in the present case it is most desirable to earth the neutral-point thoroughly, and, in addition to this, substantially to cover and enclose the whole of the rest of the parts carrying at high potential. In addition, I would say that it is most important to carry out this class of work thoroughly well. Mr. de Ferranti.

Mr. S. Evershed: I wish to add one word on the side of those who would at all events endeavour to enclose effectively all parts in a metallic sheathing, armouring, or some such device, not only on the cables, but on the gear. Mr. Evershed.

Professor D. Robertson (*communicated*): In my opinion the neutral-point should be earthed in every case, as the balance of advantages is in favour of doing so. So far as shock is concerned, an insulated system will be virtually earthed by the capacity of the system, seeing that the current required to produce a serious shock is so small, while any slight leak in one main will make the others more dangerous than they would be in a system with its neutral earthed. I fail to see how the author gets the 16 per cent. advantage in favour of the insulated system in the matter of insulation strain (pages 559 and 565). The stress between the mains is the same in both cases, and if the neutral-point of the insulated system happens to be at earth potential the stresses between each and earth will also be identical in both. But if, as is more likely to be the case, one of the mains or the apparatus connected to it is more leaky than the others, the potential of those others will differ more from that of earth than in the earthed system, and the strain in the insulation will be greater, not less than with the latter. The best use is made of the mains when they are all at equal potentials relatively to earth. If it pays to insulate one main for a certain voltage, it will also pay to insulate the others for that voltage, and the copper is not transmitting all the power it might if used at a lower one. When the neutral is earthed the potentials to earth are symmetrical, and we can have less insulation or a greater factor of safety than when they are not. The smaller liability to flash over to the metal casings with the insulated system, to which the author refers, is due to the fact that this system is very kind to its weakest part as regards insulation from earth, for it adjusts the potentials so as to throw the burden of the strain on the other mains, and no arc can be formed so long as the rest of the system is good. The fault does not cause any particular inconvenience or give any very obvious indication of its existence, and in very many cases it will be left undiscovered, or unremoved, until another develops elsewhere, when the results will be at least as bad as on the earthed system. Meanwhile, the insulation has been strained anything up to 73 per cent. above the normal, and the other mains have been in a more dangerous condition than they ought. That is the great objection to unearthed systems; even in well-conducted establishments the Professor Robertson.

Professor Robertson.

condition of having one main earthed through a fault is very apt to become the normal rather than the exceptional one. Mr. Wood's objection to the earthed system, given on page 561 and Fig. 1, is certainly not a valid one, for no one who knew what he was about would ever allow 3-phase transformers to be connected in the way shown. Unless there is a fourth conductor in the primary system joining the neutral-points of the generators and transformers, the primaries should always be mesh-connected, and certainly the double-star arrangement should never be used. The triple-frequency currents circulating between the generators running in parallel with their neutrals connected can be avoided in new systems, for it is quite easy to make an alternator whose E.M.F. wave will have no third harmonic. For a 3-phase machine it is only necessary to have 9 slots per pole, and to connect them so that any one and the *second* ones from it form one phase, instead of connecting adjacent ones, as is usual. The relative value of those harmonics whose order is a multiple of 9 will be slightly increased by doing so, but all the other multiples of 3 will cancel out. Most of the other harmonics will also be reduced relatively, the 5th, 13th, 23rd, 31st, 41st, and 49th being only about one-third as important as with a concentrated winding; the 7th, 11th, 25th, 29th, 43rd, and 47th about one-half; and the 17th, 19th, 35th, 37th, and 51st exactly the same.

Mr. Stevenson.

Mr. A. F. STEVENSON (*communicated*): Whatever one's preconceived ideas may have been, actual contact with colliery work brings one into line with the author's summing up of the case, namely, that it is generally preferable to insulate the neutral. In the event of a motor or armoured cable failing on an earthed neutral system at a time when the plant must be kept running, this can be done by removing the earth wire or bonding: the temptation is great—in fact, I have known very competent men succumb to it. In this case the motor or the armouring is in a highly dangerous condition, whereas if the neutral were insulated they would merely be a source of unpleasantness. On the introduction of leakage indicators, as ordered by the Home Office, it was found that shocks were much more severe than had been previously the case, with the result that in many cases the instrument was left disconnected, except when the inspector was about. With regard to automatic devices, my own experience is that they are only of use where the "good man" has charge of them, otherwise they will be wedged or tied up so as to stop their being a nuisance. It is in the pit where the staff is insufficient that the simplicity is needed.

Mr. Peck.

Mr. J. S. PECK (*communicated*): On page 561 reference is made to the instability of the neutral-point on star-to-star connected transformers. This is correct where three separate transformers are used, or where the 3-phase transformer is of the shell type or of the Berry type. Such transformers should never be connected star-to-star, unless the neutral-points of generator and transformers are earthed or are connected directly together, for a short circuit on any phase reduces the voltage across this phase to zero, and increases the voltage across the other

two phases to 1·73 times the normal value. As a result the transformer across the short-circuited phase runs cool, and the others usually heat excessively. The delta-to-star connection is greatly to be preferred over the star-to-star system for transformers of the above types. With the core type 3-phase transformer the neutral may be considered stable even with the star-to-star connection, for a short circuit across one phase will cause excessive currents to flow in the other phases, and so trip the breakers. With the neutral-points of transformer and motor both earthed it is possible to transmit 3-phase current in the event of one line conductor becoming open-circuited, while with unearthed neutrals, or with the neutral at only one end of the circuit earthed, only single-phase current can be transmitted with one line conductor open-circuited. On page 565, under "Stress on Insulation," the author states, "As long as the system with insulated neutral is in good order, the stress on the insulation is 16 per cent. less than on an earthed system." As long as both systems are perfectly balanced I can see no difference in the stress, whether the neutral-point be earthed or not, for the neutral-point is at earth potential, and connecting it to earth can have no effect in redistributing the stresses; but if with the unearthed neutral one of the phases has a greater capacity to earth than the others, or if there is a slight leakage to earth on one phase, the potential of this phase will fall, and that of the other two phases will rise, the limit being reached when one phase assumes earth potential and the other two the full potential above earth. Mr. Peck.

Mr. F. O. Hunt (*communicated*): With reference to Fig. 4 in the paper, and in view of the fact that there appears to be a tendency on the part of some engineers to regard leakage tripgear as a complete solution of the safety problem, it may be desirable to place on record some figures relating to the length of time which, by reason of the inertia of the switch parts, must elapse before the action of the trip-gear can cause isolation of the faulty section. By means of an oscillograph record during a short-circuit test of a turbo-alternator at a local colliery it was found that nearly three periods elapsed between "make" and "break." (The automatic free handle oil switch was driven home with a dead short already on the mains.) As the periodicity at the time was 40 per second, this indicates a duration of about $\frac{1}{15}$ second, which would be quite long enough for the ignition of gas or coal-dust if they were present at the fault. The credit for the above oscillograph record is due to the staff of Messrs. C. A. Parsons & Co. Mr. Hunt.

Mr. W. Bolton Shaw (*communicated*): There seems to be a good deal of difference of opinion, or absence of opinion, amongst electrical engineers in general on the question of earthing the neutral of 3-phase systems. I have had some seven years' experience of the working of a large 3-phase colliery plant with earthed neutral and also of a direct-current installation at the same colliery worked on the earthed concentric system, and may therefore claim to have had special opportunities of observing the results of earthing. In my opinion the advantage lies with the earthed neutral, but it should be worked Mr. Shaw.

Mr. Shaw. in conjunction with armoured cables and switch-boxes, etc., having their casing solidly connected to the armouring which should be earthed at the generator end, and so connected to the neutral. With this arrangement, a leakage to earth almost always develops at once into a short, and brings out the circuit breaker, thus isolating and at the same time locating the faulty circuit. The risk of fire from a momentary short circuit, especially when confined within an earthed envelope, is very much less than from a continued leakage. The opening of the circuit as a result of leakage has three great practical advantages over a mere indication on a leakage indicator. It stops the trouble at once; it shows which circuit is defective, and is therefore a great help in locating the position of the fault; and it prevents the circuit from being worked with the fault still on it. With the leakage indicator it is usually necessary, in order to locate the faulty circuit, to open one circuit after another on the switchboard until the faulty one is discovered, and this can seldom be done immediately without causing great inconvenience and even risk due to the stoppage of the supply without pre-arrangement. When the leakage has been located, there is a very great temptation to go on working, because it is possible to do so, rather than stop an important motor. With regard to shock, I think that the advantages claimed by Mr. Wood for the insulated neutral seldom exist under ordinary working conditions on an installation of considerable size. There is almost always a certain amount of leakage on the system from phase to phase *viâ* earth, and this is recognised by the present Home Office rules which permit a leakage current of $\frac{1}{1000}$ of the maximum supply current. The leakage indicator does not indicate the amount of this leakage but only shows if it is out of balance. When it is not much out of balance, the neutral-point will be very little different from earth potential. A person coming in contact with any one phase merely shunts a portion of the leakage on that phase, and unless the leakage is extremely small the effect on the potential difference between that phase and earth will be slight. The voltage of the shock he receives will therefore be practically the same as in the case of a system with earthed neutral. For a momentary shock 20 per cent. to 30 per cent. difference in the voltage is hardly worth considering, and in the case of a man unable to release his hold on a live conductor, it simply means that the agony may be somewhat prolonged before it results fatally. Danger from the flash due to a short is minimised in the case of switches, fuses, etc., by the flame or gas-tight cases required by the electricity rules. I am strongly in favour of using paper lead-covered armoured cables wherever practicable. I have had very heavy shorts occur on this type of cable, and it has not shown any signs outside the lead covering. Armouring does, no doubt, add to the cost of cables, but it has the great advantage of providing a substantial and visible earthed conductor to which all frames and coverings can be connected. It also adds greatly to the durability and mechanical strength of the cable, and the latter can be moved from one road to another, as is often necessary, with much less risk of

Mr. Shaw.

damage than unarmoured cable. All cables are required by the Home Office rules to be periodically examined, and there should be no difficulty in seeing where corrosion is taking place. The careless leaving of earth connections unconnected is much less likely to happen with the armouring of cables than with the small wire connections to motor frames. Where the switch and other boxes are designed so that the earth connection to the armouring is in the form of a clamp forming an integral part of the box there is very little likelihood of this happening. The size of earth wires should be determined with a view to mechanical strength as well as current-carrying capacity, and in my opinion it is advisable to have them stranded. When transmission lines having an earthed neutral are carried on iron posts it may be advisable to connect all the posts together by an earth wire which can be fixed above the line wires, and so serve as a lightning guard. The reason why I suggest this is that I had an experience of a live wire breaking away from an insulator and falling on the cross-arm, which was iron as well as the post. The post was set in the ground without concrete, but had attached to its lower end anchor or fin plates of considerable area giving a reasonably good earth contact. The voltage of the line was 3,300, but the resulting fault was not sufficient to trip the overload circuit breaker, which was set for about 80 amperes. I found on measuring the earth resistance between two adjacent posts which were 56 yards apart that it amounted to about 40 ohms, and was practically the same between posts 3 spans apart; so that between the neutral earth and any post the resistance would be above 20 ohms. In addition to this the neutral was earthed through a 12-ohm grid resistance. Taking into account the drop in voltage due to the fault, I think the comparatively high resistance of the earth circuit would quite account for the limitation of the fault within the range of the overload setting. I do not think a resistance in the earth connection to the neutral of a high-tension system serves any useful purpose. The argument that it prevents an excessive current when a short to earth occurs seems to me to be against rather than for it. In any case, a short between phases produces a much larger current, and there is no serious difficulty in coping with this. Regarding the earthing of the neutral with generators running in parallel, I have found the system of having the neutral of only one generator switched on to the earth bar at a time to work perfectly satisfactorily. There is a rather curious effect produced where generators are paralleled by a bank of lamps cross-connected direct on to the busbars. If the incoming generator is run up with its neutral earthed as well as that of the running machine, the lamps show an intermediate bright point first on one set and then on the other between the in- and out-of-phase positions. This may be mistaken for the "in-phase" position, and lead to the machine being switched in at 120° out of phase.

DISCUSSION AT NEWCASTLE, APRIL 4, 1910.

Professor Thornton.

Professor W. M. THORNTON: Mr. Wood has referred to American practice. It is quite common in America to use the "Delta" system, there being no need in that country to take the same precautions as in England. Regarding limitation of voltage, I have known fatal shocks when the voltage was as low as 80, but in underground work 150 volts would be about the point where fatal shocks begin, and therefore the voltage should not be above 120. I think it advisable to have efficient earthing in every seam, and as many earth-plates as possible.

Mr. Wilson.

Mr. J. G. WILSON: In my experience on large systems where the neutral-point is insulated, there is usually sufficient leakage to make it dangerous to touch any phase. When earthed neutrals are used, every one is aware that there is danger in touching any live part. I am of opinion that armoured cables are the correct practice, and with them there is a very strong argument for earthing. If the neutral be not earthed there will be no certainty that any cut-out will cut off the supply, but if it be earthed the supply will be cut off immediately.

Mr. Clothier.

Mr. H. W. CLOTHIER: I strongly advise earthing the neutral on the 3-phase system. With earthed neutrals it is not necessary to have a leakage indicator, which is often a nuisance. I am pleased to hear that in the case of power taken from supply companies, the author is in favour of earthed neutrals. Regarding limitation of voltage, I think about 50 or 25 volts is the best pressure for lighting in mines. I agree with the previous speaker as to the importance of armoured cables. Regarding Fig. 3, I think this makes evident the necessity for numerous earth-plates.

Mr. Hunt.

Mr. F. O. HUNT: The severity of a shock with a given frequency is a question of the size of cable employed. With regard to Fig. 2, showing leakage indicators, Mr. Wood seems to prefer the Nalder type to the electrostatic type. With reference to limitation of voltage, a case has occurred where a labourer whose hands were soaked was unable to release his hold of the conductor with a voltage of only 30. With automatic leakage trip-gear, owing to the number of parts in the automatic switch, a certain time must pass before it operates, and that time lag is more than sufficient for a flash to ignite gas or coal dust. It seems from the paper that automatic tripping devices can only be applied where the neutral-point is earthed, but there should not be any great difficulty in devising means to operate automatic trips even where the neutral is insulated.

Mr. Brown.

Mr. C. S. VESEY BROWN: The earthed neutral is a good fault-finder. Personally, I always earth, but I often have great difficulty in obtaining a good earth connection.

Mr. Porter.

Mr. G. L. PORTER: It is possible that the drop near the earth-plates may be due to the cross-sectional area of the current path near the plates, and not to electrolytic effects.

Mr. Wood.

Mr. W. W. WOOD (*in reply*): I am glad to see that although a number of speakers are in favour of invariably earthing the neutral of any

Mr. Wood.

colliery plant, several of those more intimately connected with mining work agree with my conclusions that each case should be considered on its merits, and no such hard and fast rule laid down. There seems to be rather a tendency to consider the question from too narrow a standpoint, and to assume that all colliery installations are of large size, supplied at high pressure, and run on the lines of a supply station. It must not be forgotten that there are a very large number of low-tension installations of small size, and that the conditions under which a colliery generating plant is run vary widely from those of the average central station. Local considerations affect the working of almost every colliery, and while I have been interested in the various criticisms of my paper, no arguments have been put forward in the discussion which would lead me to alter my original conclusions. Mr. Wilson points out that there is a possibility of receiving shock from touching one conductor and earth, even on a completely insulated system, due (1) to the tendency of the neutral point to remain fixed owing to the capacity of the system and (2) to the fact that there must be slight leakage on other phases of any practical installation. Both of these points were referred to in my paper, but Mr. Wilson as well as several other speakers fail to mention with regard to (1) that the current which could traverse even a body of no resistance cannot exceed the charging current, and on many colliery plants would be only a few milliamperes. Now, if shock is received (as in the case of making contact with one phase and earth, on an earthed system) with plenty of power behind, when once the resistance of the skin is broken down a heavy current can traverse the body, giving a comparatively high-current density throughout it, and great tendency to damage vital parts. Again, even when the skin is not damaged considerable current can flow if a large area is in contact with the electrodes. When, however, the current that can possibly flow is limited (as in the case of capacity effect, or slight leakage on other phases) conditions are very different, as a small current has the large area of the body to carry it, with consequent reduction of current-density and of danger of damage to vital organs. Mr. Chattock, in the discussion of Mr. Rider's paper recently read before this Institution, mentioned several cases in which workmen had made contact with the outer of even high-tension insulated systems and earth, and survived the effects, while on a system with earthed neutral they would certainly have been killed.

In many cases, therefore, while the leakage or capacity-current would be sufficient to deter any one from treating live terminals with contempt, it is obvious from the reasons given above that with an insulated system there is undoubtedly less danger of fatal result from shocks to earth.

With regard to the protection afforded by leakage trips against explosion caused by damage to cables carrying current, it must be noted that armoured cables are necessary to make the trips effective, and that the results of the experiments referred to by Mr. Wedmore show that in any case it is difficult so to damage an armoured cable as

Mr. Wood. to produce flashing externally, and further than this, no case is on record of any fire or explosion caused in this way. In addition, these devices depend absolutely on the continuity of the armouring being maintained, and as the water in many collieries attacks armouring and eats it away very rapidly, it would be very inadvisable in such pits to install armoured cables or to rely on them for operating leakage trips. Mr. Clothier refers to what he describes as contradictory advantages claimed for the rival systems of earthed *v.* insulated neutral, but it is one of the points in favour of considering every case on its merits, that the advantages of either system considered from another point of view may be its disadvantages also.

The question of leakage trips and explosion I have dealt with above, and the comments on Fig. 1 I shall refer to later. Fig. 3 is intended to show the necessity for a number of earth-plates, and that an earth wire to bank, without earth-plates in every stratum, may be a serious source of danger. Incidentally it again illustrates the point that where with earthed neutral dangerous conditions may occur, if the neutral be insulated an additional safeguard is present. It is necessary again to distinguish between (1) earthing the neutral and (2) putting down a number of earth-plates and having an earthing system with connections to all metallic casings, a practice I strongly recommend. The fact that in Fig. 4 only an earth-wire and no armouring is shown has been criticised by several speakers. This was done to make the diagram clearer, and exactly the same conditions hold good whether an ordinary earth-wire is used, the armouring of the cables, or any other method of earth connection. The real point is that as long as the earthing is good it is not possible to get a shock either with an earthed or insulated neutral, but the moment the earthing fails dangerous conditions arise which are more dangerous with the earthed neutral, and against which the leakage trip is no protection. The necessity for a mechanically strong earth-wire protected from corrosion seemed so obvious that I omitted to call attention to it. I regret that I did not give a fuller reference to the source of my extract from President Charles Scott's remarks on earthing the neutral, but Mr. Patchell has supplied this, and although his (President Scott's) remarks were made in 1903, conditions are still very much the same, if one is to judge by the paper recently read by Mr. Marchant and Mr. Watson before this Institution.* Speaking of high-tension transmission only, after giving various theoretical advantages of the star connection they state: "In spite of this, however, delta connection is very much more common than star, and at the Great Western Power Company's Station, where a change from 60,000 to 110,000 volts was made on October 1, 1909, the connection was altered at the same time from star to delta. No practical difficulty of overheating due to circulating triple frequency current appears to be met with in this arrangement, nor does the variability of the neutral point appear to have any appreciable effect on the working of the system."

* *Journal of the Institution of Electrical Engineers*, vol. 44, p. 423, 1910.

I am glad to see that Mr. Patchell and Mr. Mountain agree with the conclusions I have put forward. Mr. Wood.

Mr. Snell certainly describes a very ideal system, but one which in many cases would involve an unnecessary expense, and probably bar the use of electricity in many places where it could be advantageously and safely employed.

In connection with Mr. Wedmore's remarks, I have also spent a good deal of time going through the Home Office reports, and a point that struck me very much was, that if a man was killed by a fall of roof or was crushed between tubs not much notice was given to the matter, but if he was killed from electrical causes it attracted an altogether disproportionate amount of attention. The fact that during 1908 approximately 1,280 people were killed in mines and collieries from all causes, and only about 14 from electrical causes (of which 14 some were pure accidents and some wilful carelessness), conveys more to the mind than the statement that the deaths from electrical causes average about 1 per cent. of the total deaths.

Replying to Mr. Sayers's challenge to Fig. 1, if he will refer to the discussion which took place on a paper presented to the American Institution of Electrical Engineers by Mr. F. O. Blackwell, he will see that Mr. P. N. Nunn, the engineer of the Telluride Power Company, stated that the conditions described in this diagram not only could occur, but frequently had occurred on his system, which was connected as shown on this diagram, and several other speakers also confirmed this. The reason the lightning arresters arced over and were the first signs of anything wrong was because these arresters were set for the normal working conditions of a maximum voltage of 58 per cent. of the line volts between any point and earth, and owing to the abnormal conditions which had arisen there was, as a matter of fact, the full line voltage between the two phases and earth. I do not recommend the connections shown in Fig. 1, but have called attention to them to show that before relying on an earthed neutral for protection it is necessary to consider fully the local conditions of every case.

In reply to the point raised by the same speaker as to the advantage of the earthed neutral enabling the designer to know the exact voltage which he has to deal with, and distributing his insulation to meet the same, this of course is quite the case on extra high voltages, but on the average colliery voltage, say either 650 or 3,000 volts, the difference to the designer is quite negligible.

With regard to Mr. Wordingham's suggestion that there should be no half measures, and the neutral earthed with as low a resistance as possible, such a practice seems more suitable for a supply station than for the average colliery installation, where the object is to reduce any liability to flashing or arcing underground as much as possible.

Replying to Professor Robertson, in a system with insulated neutral the tendency for current to flow between phases, due to the line voltage, is resisted by two equal sets of insulation in series. With earthed neutral, line volts/1·73 are only resisted by one set of insulation,

Mr. Wood. hence the stress in the latter case is approximately 16 per cent. greater. This is a minor point, but I do think it of considerable importance that where the neutral is insulated there are two sets of insulation in series, both of which must fail to produce the same dangerous results as are obtained by the failure of one such set of insulation with earthed neutral, and that the leakage indicator, which is required by the Home Office regulations on insulated systems, shows when one of the two sets of insulation becomes defective. Even when one pole is completely earthed conditions are now just the same as on an earthed system before its insulation fails, with the exception that the voltage to earth is now, say, 500 instead of 290, a fact which makes very little difference indeed to the insulation, or to the danger of fatal results from shock, as I pointed out in my paper. Where, however, 6,000 volts is in use this difference in voltage becomes relatively more important in influencing a decision as to whether to earth or insulate.

I am interested to see Mr. Shaw's experiences, and I have already dealt with most of the points he raises. In the matter of shock, however, the real question of moment is not the voltage, but how much current flows through vital parts of the body, and as I have already pointed out, when this current is limited by being only due to capacity or to slight leakage on other phases, any danger is reduced to a minimum.

In discussing the question of earthing the neutral, one is of necessity drawn into considerations as to earthing generally, and several of the diagrams were prepared to illustrate points in both subjects. A number of speakers seem not to have quite understood my attitude towards earthing, although I endeavoured to make this clear in my paper, so that I again emphasise my opinion that while the question of earthing the neutral is often a very open one, it is impossible to lay too much stress on the importance of protecting live parts, and of properly earthing metallic casings containing such parts. As long as such earthing is properly carried out danger of shock is negligible, but it is not sufficient to rely on a single earth-plate, but preferable to have a continuous earthing cable with earth-plates in every level, and if possible at every motor.

The Chairman. The CHAIRMAN: I think we should congratulate Mr. Wood on having succeeded in eliciting such a good discussion. I am sure you will join with me in according him a hearty vote of thanks by acclamation.

The resolution of thanks was put and carried by acclamation.

Proceedings of the Five Hundred and Ninth Ordinary General Meeting of the Institution of Electrical Engineers, held in the Rooms of the Royal Society of Arts, John Street, Adelphi, W.C., on Thursday evening, May 5, 1910—Mr. S. EVERSHED, Vice-President, in the chair.

The minutes of the Ordinary General Meeting held on Thursday, April 28, 1910, were taken as read, and confirmed.

The following paper (see p. 590), "A Telephone Relay," by S. G. Brown, Member, was read and discussed.

The meeting adjourned at 9.55 p.m.

A TELEPHONE RELAY.

By S. G. BROWN, Member.

(*Paper received March* 16, *and read in London on May* 5, 1910.)

This paper deals with the telephone relay and its various applications. The relay is the outcome of six years' study, but has only been brought to its final form during the last eighteen months. Ever since the introduction of the telephone a real need was felt for a telephone relay when it was discovered that the distance over which telephones could be used was comparatively limited. Many inventors have worked on the problem, and it has been declared by eminent telephone engineers to be insoluble. One of the American telephone companies offered a million dollars some years ago for a telephone repeater, but no one has gained the reward.

Edison, soon after his invention of the carbon button transmitter, caused an electromagnet to act upon the iron diaphragm and thus turned it into a relay, but it was not a success. Hughes, in his paper before the Royal Society in 1878,* describing his extremely delicate microphones, stated that a telephone receiver, if included in the microphone circuit and placed upon the resonant board, caused a continuous sound to be produced. It follows, he says, that the question of providing a relay for the human voice in telephony is thus solved. Unfortunately it was not solved ; he had shown how to make a relay that would magnify a noise or musical note, but not one that would intensify articulate speech.

Sir Oliver Lodge,† in a paper read in December, 1898, before this Society, described a relay, consisting of three or four reeds or tuning forks, each carrying carbon contacts and working in series with one another. Each reed was arranged to resonate to one particular musical note, and when this note was passed through the string of relays, it was multiplied in power to a considerable extent. An instrument of this character, however, is not effective in intensifying speech. An articulate relay must have its vibrating parts damped, or, in other words, possess no resonating properties ; it is therefore far more insensitive to sound than one that is arranged to resonate to one particular note.

The invention of the powerful granular transmitters of the Hunnings type stimulated further efforts to obtain the speaking relay, and some

* *Proceedings of the Royal Society*, vol. 27, p. 362, 1878.
† *Journal of the Institution of Electrical Engineers*, vol. 27, p. 799, 1898.

progress was made with this type of microphone, particularly in America. I will not describe these relays further than to say that they consist in combining the telephone receiver and the granular carbon transmitter; both of these are designed as efficiently as possible, and in some cases automatic means are provided to shake up the granules should they become packed. These relays are only partially successful. Their advantages are not decisive. They require relatively powerful currents to work them; that is to say, when the telephone currents become sufficiently feeble to require their services, it is at this point that the carbon instrument fails to work. The telephone relay to be successful has to magnify in a continuous manner varying currents that are too feeble properly to affect a Bell telephone receiver. Such currents would be of excessive weakness, say of the order of the one hundred millionth of an ampere (10^{-8} ampere), and the mechanical movements produced by such currents, which have in their turn to bring about the increased electrical changes, are therefore microscopic in dimensions.

The author's telephone relay has had to be developed along quite new lines. It takes as its basis the researches of J. J. Thomson, Earhart, Kinsley, and others, with regard to the flow of electrons across a microscopic air-gap between two conducting surfaces at different potentials.* Earhart made a series of experiments on the difference of potential required to produce sparks whose length is comparable with the wave-length of sodium light, and he found that when the distance between the metal electrodes falls to less than about 3×10^{-4} cm., the spark potential falls off rapidly with the distance, and seems to become proportional to the distance; that is to say, when the electrodes are placed very close together, within a distance such that the average intensity of force F between the electrodes reaches a value of about a million volts per centimetre, the discharge or current passing is determined by the condition that F, which is V/d, reaches this value (where V is the potential difference, and d the distance between the electrodes). If the metallic circuit of a dry cell be interrupted by a minute opening or space of the order of 5×10^{-7} cm., the metal at the point of interruption being platinum, the current will continue to flow round the circuit and across the opening, and any slight alteration in the length of the space, which I shall call the conduction space, will vary its resistance and greatly affect the value of the current that flows round the circuit. This conduction space is therefore exactly what is wanted for the current-varying device of a telephone relay, where microscopic mechanical movements are to be transformed into large current changes. The dimensions of the conduction space are so small that it is difficult to ensure and maintain it by direct mechanical means. The current that flows across the space was therefore made to do its own adjustment, very much in the same way as the current that passes through the arc of an arc lamp is made to strike and maintain the length of the arc.

* See "Conduction of Electricity through Gases," J. J. Thomson, chap. xv.

Fig. 1 is a side view of the instrument with the brass cover removed. N is a permanent magnet, continued by soft iron poles right up to but not touching the "invar" steel reed P. Round the soft iron pole extensions are wound the two sets of coil windings H and K. The telephone currents to be magnified circulate round the winding H and thus by varying the magnetism set the reed P in vibration. M O are the top and bottom metal contact-pieces, which are opened to an infinitesimal degree to form a microphone by the fine adjusting screw W and by the action of the local current passing through the contact and round the winding K. It is by the action of the local current operating through this winding that the conduction space is formed

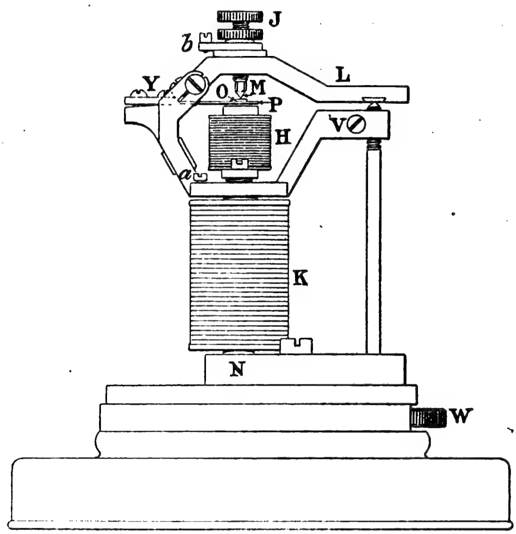

FIG. 1.

and afterwards maintained. So good is the automatic adjustment that the instrument may be turned upside down, producing hardly any noticeable alteration in the value of the local current and without any effect on the working of the relay. The regulating winding K must not act when traversed by the rapidly varying telephonic currents; this is brought about by surrounding the iron under the coil by a closed circuited copper sheathing. Eddy currents set up in this sheathing by mutual induction destroy the self-induction of the coil.

Fig. 2 is an enlarged view of the reed P and the contact-pieces M O. In the present instrument the contact is made between metal pieces of hard osmium iridium alloy. The top contact is pointed, the lower one is flat and is soldered to the reed, both are polished and work under a small drop of thin oil.

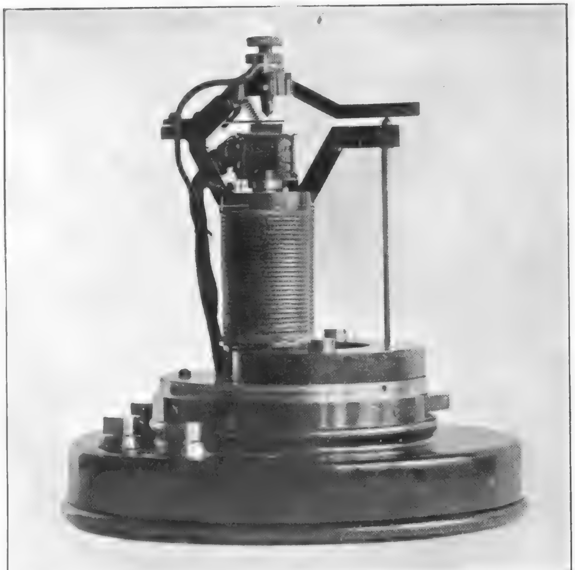

FIG. 6.—The Telephone Relay.

FIG. 7.—Telephone Relay in Brass Case with Upper Arm raised for Cleaning the Contacts.

In earlier instruments the lower contact O was carried by a thin iron disc, the relay was then very susceptible to outside noises. For this reason a reed is now used; it exposes such a small surface to the air that it is practically unaffected by extraneous sound.

Fig. 3 shows the connections of the relay. C is a dry cell (this is the normal voltage, which is as high as it is desirable to employ), K the low resistance regulating winding, T the receiving telephone or telephone head-piece of approximately 40 ohms resistance, D is an amperemeter or current indicator; when the microphone contact is opened so as to cut down the local current to half its maximum value the relay is usually at its best adjustment. The telephone currents to be magnified enter by the terminals marked A and circulate through the winding H.

The relay will magnify the very feeblest telephone currents. Speech or signals that are too faint to be heard in the ordinary Bell receiver may be heard clearly through the relay. If a watch

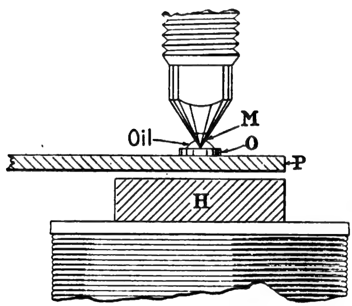

FIG. 2.

be held against the ear-piece of a Bell telephone the induced currents produced when passed through the instrument will reproduce the ticking in the receiver attached; this is a severe test.

This property of magnifying feeble telephone currents has made it particularly useful in wireless telegraphy. On replacing the telephone by the relay the increased sensitiveness thus obtained doubles the distance over which it is possible to receive signals. Its utility in this direction has been tested among others by the Admiralty and the Post Office. In a wireless receiving station, messages, the very existence of which was not even suspected, owing to their extreme feebleness, when listened for under former conditions with the relay in circuit, were easily read. At the invitation of Mr. Marconi I took two instruments to the Haven Hotel, Poole. In one of the tests (Clifden, in Ireland, sending with the Marconi musical spark) the signals were heard in the telephone, directly connected, as a faint but clear and pleasing series of musical notes. But with two relays joined to the system and working in series

the notes were rendered so loudly as to be heard clearly by every one in the room, and an operator listening at a distance of several yards from the instrument could have deciphered the message. The relay is not easily affected by extraneous noises and vibration. It can thus be carried on board ship and worked in all weathers.

As regards its utility on ordinary telephone lines, speech may be magnified many times in loudness without preceptible loss in the articulation, and it will work with large currents to a point at which the Bell receiver in its local circuit is responding with uncomfortable loudness. In experimenting over a 20-lb. standard cable and speaking only one way, it has been proved that, when the relay is applied, 30 miles may be added to any length through which it is possible now to speak direct. For instance, supposing the length of the core for direct speaking be 20 miles, this may be increased to 50 miles

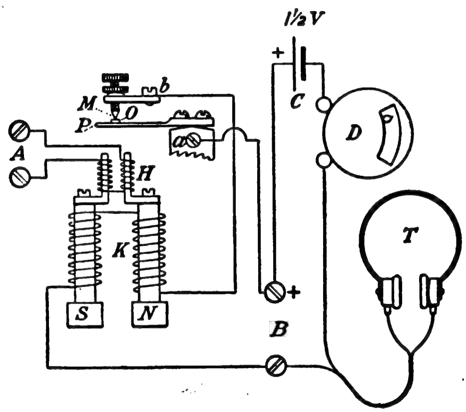

FIG. 3.

for the same loudness and approximate clearness when the relay is in circuit, either as a single repeater at the end of the first 20 miles, or as a receiver at the end of the 50 miles.

These tests prove that the telephone currents must be increased in strength to the extent of something like twenty times. If still greater magnifications are required than can be obtained with one relay, the simplest method would seem to be to employ two relays working in tandem. Their combined power would then be 400 times. In the majority of cases it is not necessary to add to the natural electrical damping of the reed, but if a piece of soft rubber be made to touch it, the voice can be transmitted with greater clearness even than if the conversation were taking place ordinarily in a room. This may be due to the complete absence of echoes.

By means of the local regulating winding (see Fig. 2), the metal contact M O is transformed into the most exquisitely delicate micro-

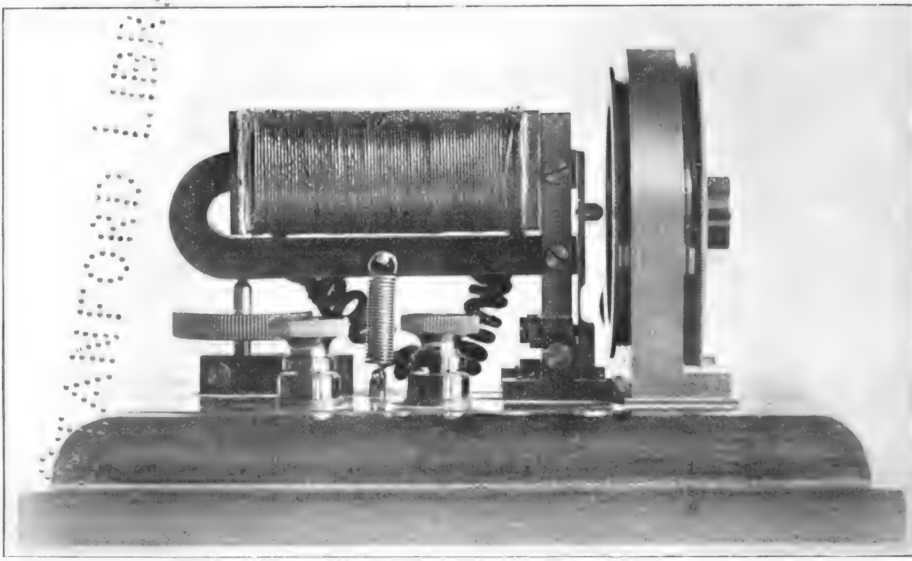

FIG. 8.—Electrical Stethoscope.

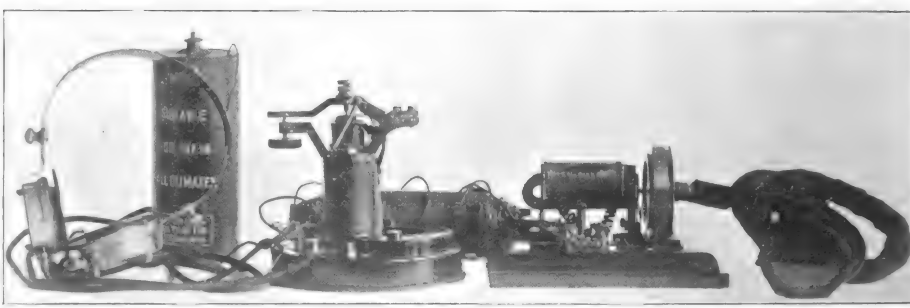

FIG. 9.—Electrical Stethoscope and Telephone Relay ready for Use.

phone, more sensitive, there is every reason to believe, than could be formed by light pressure between carbons. Such a microphone has rendered possible the construction of an electric stethoscope, an instrument by the use of which the sound of the heart or other internal organs may be greatly magnified. This, I have been informed, may render it possible to detect in the earlier stages, heart disease, aneurism, and gall stones.

Fig. 4 is a diagrammatic illustration of the stethoscope. A is the front part and consists of a shallow brass cell faced by a thin ebonite diaphragm. A is placed upon the part of the body to be examined, say the heart; the beating of the heart is communicated to the ebonite diaphragm, then to the air inside the tube B, and thus the metal diaphragm D is set in vibration. M O, as before, are the osmium-iridium contact-pieces. M is mounted on the diaphragm, and O on the steel

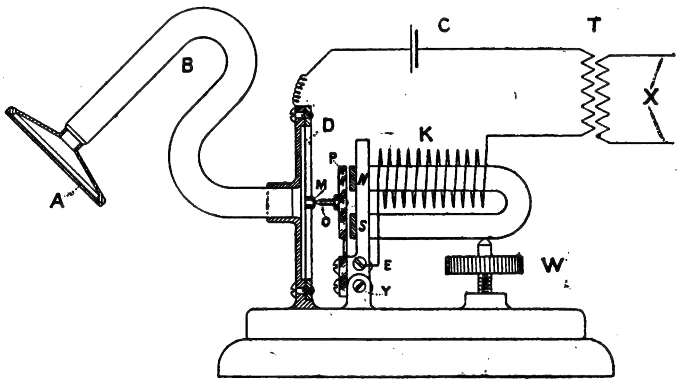

FIG. 4.

reed P. The magnet N S and the reed are carried by a brass frame E, which is pivoted or hinged at the lower support Y. The conduction space is formed between the contacts M O by turning the fine adjusting screw W, and by the automatic action of the local current from the cell C flowing through the winding K and round the magnet. T is a special telephone transformer of equal windings of, say, 20 ohms resistance in the primary and in the secondary.

The electric stethoscope in its present form causes the sound of the heart to be three times as loud as in the ordinary stethoscope. This is scarcely sufficient for practical purposes. But if a telephone relay, such as I have previously described, be attached to the wires x of the transformer, the two instruments combined raise the intensity of the sound some twenty times and more, and this is ample for all ordinary purposes. The sound to be examined is picked up by the end of the tube A, and is heard in the telephones of a head-piece attached to the relay.

At the invitation of two physicians I took the complete instrument,

stethoscope and relay, to the London Hospital, where it was tested upon a number of diseased heart cases. Not being a doctor myself, I cannot discuss the merits of the instrument with regard to its medical value, except to say that it seemed to render diagnosis particularly easy and revealed some phenomena only previously suspected. From a sound magnifying point of view the general results were as follows: When the instrument was applied directly to the heart the sound of the beats given out in the telephones was uncomfortably loud, and easily heard by the patient and all those that stood round, and this even if the telephones were in position on the head of the operator. The stethoscope as used increased the heartbeats to the almost complete exclusion of the shriller or breathing sounds. This has been brought about by mechanically tuning the disc D and the reed P of the telephone relay to the corresponding low note, and by a proper proportioning of the volume of air enclosed by the tube B. On other occasions, during private experiments, the instrument has been tuned so that nothing but the breathing sounds were audible, the passage of air through the lungs was heard as the roar of the wind through a forest of trees. This power of discrimination should be of service in allowing the independent examination of various organs of the body.

Replacing the telephone head-piece by a transformer, the stethoscope has been joined to the telephone service in my house, and for the sake of experiment, the sound of the heart has been transmitted over several miles of telephone line to doctors in various parts of London and to other friends who were interested. All of them reported that the sounds received in the telephone were as loud and clear as when heard locally. The line, therefore, does not appear to produce much loss or distortion. This trial proved that it is now possible for a specialist, say, in London, to examine a patient, say, in the country, stethoscopically, and to arrive at a correct diagnosis.

The instrument must of necessity, to replace the ordinary stethoscope, be more sensitive to sound than the human ear. This is proved by slight noises made in the room being heard in the telephones as loud noises. In consequence of this, the apparatus is padded and guarded as far as is possible from all outside disturbances, and the patient should be examined in a quiet room. If the instrument is provided with a small funnel in place of the tube B, it will pick up and magnify the slightest sound, and ordinary speaking may be increased to a deafening shout in the telephone. Such an instrument, when properly constructed for the purpose, may be of use to those who are afflicted with deafness.

The relay has been used on the electrophone system, and by its aid, damping the reed with a piece of rubber, the speaking and music from the theatres are rendered with loudness and greater clearness than it is possible to have on the telephones supplied by the company, and by adding a loud speaker with trumpet the sounds can be heard in the room.

I come now to a subject that is interesting me greatly—it is still a matter of experiment—the production of a clear and loud-speaking transmitter. Such an instrument would give considerable comfort to the subscriber, and might save hundreds of thousands of pounds worth of copper for the companies. I am under the impression that the carbon transmitter has been developed to its full extent, ceaseless efforts having been directed to this end by the engineers of the large telephone companies.

To make progress towards an ideal transmitter, carbon had therefore to be abandoned, not because of any serious defect in its microphonic qualities, which are good, but because of its bad conducting power. It would not transmit enough energy. One must pass much current in order to speak loudly, and a material was wanted that not only would conduct well, but would change its resistance to pressure more readily than carbon. I am pleased to say that I have discovered something that carries out my wishes well in both of these directions. To indicate that this discovery is a novelty, is quoted the following from Preece and Stubbs' "Manual of Telephony" chapter on carbon transmitters :—

> "Ceaseless efforts have been made by some of the most able of investigators to discover some material other than carbon that was equally efficient—efforts that if they had been crowned with success during the continuance of the monopoly of the use of carbon would have ensured a handsome fortune. Hitherto nothing has been found that even approaches carbon in efficiency for microphonic purposes, and now that the monopoly has lapsed the incentive to investigation is considerably reduced."

Again, in Miller's "American Telephone Practice," 1905 edition, chapter on the carbon transmitter :—

> "Many vain attempts have been made to discover a satisfactory substitute for carbon as the variable resistance medium in telephone transmitters, the patents on the use of carbon electrodes having at first formed one of the mainstays of the American Bell Telephone Company's great monopoly."

During some experiments with the telephone relay attempts were made to dispense with the regulating winding and form the microphone by the mere pressure of the electrodes one against the other as with carbon. With gold, platinum, palladium, and rhodium, it was not possible to do so. On the contrary, a microphone could be formed by light pressure between the following : Iridium, ruthenium, osmium, and osmium iridium alloy. They are arranged advancing in the order of their effectiveness, which likewise is the order of their hardness. With iridium the action was only just shown, while osmium iridium alloy makes a microphone that can carry large currents, stand high

temperatures, and is exceedingly sensitive to small changes of pressure. This alloy is by far the best of the whole series, as it is the hardest, and although expensive, can be readily purchased as natural grains or granules, sifted to any desired uniform size. As regards the effectiveness of carbon, I should be inclined to include it in the series between iridium and ruthenium. The chemical properties of carbon, ruthenium, and osmium have likewise much in common, in that they resist the action of all acids, and are carried off as a gas by oxygen when strongly heated.

Ruthenium and osmium are of little value for microphonic purposes if purchased in their commercial form as grains or powder. The grains must be first fused into a bead and then crushed into granules. This may account for the failure of previous experimenters who, in their endeavour to compete with carbon, tried nearly everything that could be mentioned, including ruthenium and osmium, but without success.

Several "solid back" transmitters have been taken and altered in various ways to make use of the new metal. In one case the ordinary carbon electrodes were entirely removed and replaced by sheet iridium-faced ones $\frac{3}{16}$ in. in diameter; these electrodes were separated by a distance of $\frac{1}{20}$ in., and the space between was nearly filled by 3 grains weight of very fine granules of osmium iridium kept in place by a rubber tube. This new transmitter would take permanently a current of $\frac{3}{4}$ ampere from a 2-volt accumulator. It was connected to the telephone service through a large transformer, which had a low-resistance primary of only $\frac{1}{10}$ of an ohm. The ordinary carbon transmitter, supplied in the usual way from the central battery, was kept in position in series for purpose of comparison. The results of several trials were as follows: Speaking on both occasions with equal force, first, directly into the mouthpiece of the carbon transmitter, secondly 12 in. away from the mouthpiece of the metal transmitter, the same volume was given in the receiving telephone. When the new transmitter was spoken into at a distance of 3 in. the sound was two or three times louder than is at present normal, and when spoken into directly, the sound at the far end was uncomfortably loud and the voice could be heard with ease 3 yards away from the receiver. In all cases the articulation was clearer and crisper with the metal than with the carbon transmitter.

The first difficulty to contend with occurred after the instrument had been in use some months. This was a gradual weakening of the power of transmission, which was eventually found to be due to the iridium faces of the electrodes becoming superficially oxidised. To remedy this the iridium has been replaced by gold, which so far has proved satisfactory. Another improvement was to cone inwards the faces of the gold electrodes; this is to prevent the granules from unpacking, as they had previously a tendency to do when worked between plane faces.

An osmium iridium granular transmitter has been constructed

embodying all these later improvements (see Fig. 5); the electrodes have a diameter of $\frac{1}{4}$ in., and it will work permanently with 1 ampere at 2 volts. When joined to the telephone circuit and spoken directly into, the distant receiver will respond with overpowering loudness. Such an instrument could be fitted in subscribers' premises where long-distance telephony was much in use, and distances could be spoken over which at present offer considerable difficulties. Up to the present no regular long-distance tests have been made, but it has been tried over 60 miles of 20-lb. standard artificial cable, and will work over this length with clearness and reasonable loudness, showing that this was by no means the limit. In all these trials a local battery was used. As most of the transmitters in London are supplied with current from common or central batteries at the exchanges, it would be im-

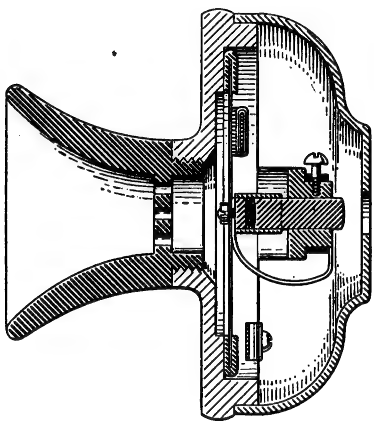

FIG. 5.

portant to adapt the new instrument to this system, but up to the present nothing has been done in this direction. The metal transmitter has a low resistance; this would have to be raised by a suitable design to make it really successful. The amount of current received over the telephone wires at my house is only 0·06 ampere, supplied by, I believe, a 22-volt accumulator, working through the 360 ohms of the line. On one occasion, as an experiment, the central battery carbon transmitter was replaced by an ordinary low-resistance metal one, and at the far end clearer speech was obtained, which was as loud as before. The upper harmonics of the voice are more faithfully transmitted by the metal granules than by the carbon—this accounts for the superiority in the articulation. As metal replaced carbon in the incandescent lamp to improve the efficiency, it would be curious if it should be doing the same thing now with the telephone transmitter. A much smaller quantity of the metal powder or granules is required as compared with carbon, and its sensitiveness in resistance to small changes of pressure

is much greater; the new material is therefore peculiarly adaptable for the purposes of a relay for use on telephone lines where moderate magnification only is required. Such a relay has been constructed using osmium iridium powder as the resistance varying medium; it is simple in design, requires no adjustment, and so far gives a moderate magnification with good articulation.

Before closing this paper I wish to acknowledge my gratitude to Messrs. Johnson and Matthey for helping me to secure specimens, to Sir William Crookes for the gift of several rare and intensely hard alloys, and to the officials of the Post Office and the National Telephone Company for facilities for trials.

All the experiments mentioned in this paper have taken place in my private house, and my wife has been my only assistant.

APPENDIX.

Referring to the telephone relay, the efficiency of the microphone for speech transmission depends largely upon the metal employed for the contact. Experiments have been made with the following results. The metal must be unoxidisable. Thus materials like brass and aluminium are useless. If they partially oxidise like steel and silver, the magnifying power is small. With the following, good results were attained: Pt, Pd, Rh, Ir, Ru, Os, and osmium iridium alloy. Carbon has been tried for one or for both of the contact-pieces; the magnifying power is then smaller than with the metals, and less current can be sent through, due to its greater specific resistance. Gold, due to its complete absence of surface oxidisation, makes an unstable contact, and the relay will buzz, very much after the fashion of an electric bell, under all ranges of adjustment. (Soft pure gold makes the best contact for an ordinary relay of any material that I am acquainted with.) Even with the metals of the platinum group the relay can be made to buzz by cleaning the contacts with a cloth, but stability of working can be again secured by oxidising the surface, by exposure to the air, or, what is much better, by applying thin oil to the surfaces of the contact. The nearer the relay is to this buzzing point the greater its sensitiveness; it is therefore advisable to clean the contact so as to obtain the buzzing action and to stop the action by the application of a small drop of thin oil. The harder the contact metal used the clearer the speech through the relay. With soft platinum the higher harmonics are more or less absent, but with osmium iridium the articulation is quite clear and crisp.

Microphones are sometimes liable to produce faint bubbling and squeaking sounds; this is due, I think, principally to want of hardness in the contact-pieces, especially if the upper bruises the lower piece. This sound can usually be stopped by shunting momentarily through a suitable resistance the winding of the local circuit. A microphone formed between two hard metals can touch only in one spot. As half the

energy liberated from the local battery is normally dissipated at this point, the rise of temperature there may be very considerable. This heating puts a stop to any great handling of power by a single contact. For these reasons it is not advisable with the normal voltage to pass more than, say, $\frac{1}{4}$ ampere; if the currrent is too great the sensitiveness will decrease with time; but if the current is kept small, say of the order of $\frac{1}{20}$ ampere, the delicacy may be perpetually maintained. It is fortunate that the harder varieties of the platinum group are the ones that are able to stand the higher temperatures.

The following rough tests of a special form of telephone relay may be of interest, the resistance of the coil through which the current to be magnified passed was in this case 1,000 ohms. 0·126 milliampere switched on through this coil caused the local relay current to vary from 3 to 0·5 milliamperes, the contact volts from 0·36 to 1·19, the contact resistance, as calculated, from 120 to 2,370 ohms, and the measured movement of the reed at the place of contact 8×10^{-6} in. With the contact open and no local current, placing a 10-gramme weight on the reed near the contact produced a measured movement of $2{\cdot}4 \times 10^{-5}$ in. With the contact adjusted to pass 4 milliamperes, the 10-gramme weight cut the local current down to 1·5 milliamperes and produced a movement of $1{\cdot}2 \times 10^{-5}$ in., and with 25 milliamperes the same weight reduced the current to 20 milliamperes and caused a movement of $0{\cdot}6 \times 10^{-5}$ in. We have thus the curious effect, that with a given applied force, increasing the local current cuts down the movement of the reed. Perhaps this accounts for the fact that, within wide limits, altering the resistance and thus the value of the current in the local circuit does not seem to change the magnifying power of the relay; this power is more a question of contact and voltage than anything else. If a telephone relay is required to have a high degree of sensitiveness the voltage of the local cell must be reduced to, say, half a volt. This low voltage can be secured by opposing an accumulator to a dry cell, but the arrangement can only be at the expense of the self-regulating power of the microphone.

A telephone relay, if placed simply in the middle of a long telephone line, can magnify the currents only in one direction—such a device is called a single repeater. The relay for practical use has therefore to be associated with balancing coils and placed in the line so that it may work in either or both directions—such a combination is termed a two-way repeater. In a two-way repeater the lines on each side of the coils have to be balanced one against the other, and anything that produces a variation, say leakage, will cause the relay to react upon itself and thus interrupt the conversation till the balance has been restored. Theoretically it would seem that the two-way repeater can be only one-quarter the efficiency of the single repeater. Although the one-way relay is now solved it will be seen that there is still much to be done before the two-way repeater is practicable.

Discussion.

Mr. Evershed.

Mr. S. EVERSHED : I remember that on the last occasion when I attended a meeting of the Institution in this room we had a paper by Messrs. Cohen and Shepherd on telephony;* a paper which, so far as I know, gave the first clear account of the nature of telephonic speech currents. I feel sure that paper gave a great impetus to the progress of telephony. Now it is our good fortune to hear about another development of telephony in connection with the two instruments which Mr. Brown has brought before us. I confess to a keener interest in the relay than in the metallic transmitter, but all the same I am delighted to find that Mr. Brown has gone away from carbon and got a metallic transmitter so full of promise. To use something besides carbon is to break new ground, and that is what is wanted in telephony. The author has dealt with the transmitting end, but I should like to urge him to deal also with the other end. The receiver is precisely what it was when Graham Bell finished it; it has remained practically untouched ever since. To my mind it is almost useless to devise a transmitter capable of dealing with large currents, and imagining that the present receiver will deal with them successfully, because as soon as we try to increase the amplitude in the Bell receiver, we shall decrease the articulation. What is wanted is a receiver which will give the greater amplitude without any sacrifice of the articulation which we now get from the Bell receiver.

Mr. Taylor.

Mr. J. E. TAYLOR : It is some three or four months since I had the first opportunity of seeing what the Brown telephone relay was capable of. That was on a wireless telegraphy installation. I may say that on that occasion I was not so much impressed with the qualities of the instrument as I had hoped. That it did magnify the sounds, and that very considerably, was very evident, but it appeared to be a little unstable in its action. However, on being able to give a little closer attention and a little more time to the instrument later on, my views were considerably modified. I found that provided one can get suitable points and a good instrument to start with it will maintain its adjustments and keep its magnifying properties to a very pronounced extent without a great deal of variation, and I can testify to the fact that it is capable of picking up wireless telegraph signals which are entirely inaudible on the ordinary telephone receiver. Signals which are just audible may be very considerably magnified, probably something in the nature of twenty times, as the author has told us to-night. I am under the impression that the reason the instrument did not behave so well on the first occasion, when I had the opportunity of trying it, as on the second was that or some reason or other the upper contact point had become slightly flattened. I should like the author's opinion as to whether great attention and care need be paid to getting the point of the upper contact as perfect as possible in order that the magnifying power of the instrument may be properly maintained and its reliability

* *Journal of the Institution of Electrical Engineers*, vol. 39, p. 503, 1907.

and constancy assured. I also had an opportunity of listening to the author's new form of microphone a short time ago at a private rehearsal, and was certainly very much struck with the volume of sound which it is possible to attain at the end of an artificial cable representing 60 miles of standard cable. The audibility was much greater than with any carbon microphone I have ever heard. It is a little early to predict how much real utility there may be for these appliances, either the telephone relay itself or the metallic granule microphone, but the instruments are certainly most interesting and very suggestive of future progress. Mr. Taylor.

Mr. B. DAVIES : In the author's relay and transmitter I believe we have something that is really new, and are apparently treading on entirely new ground. The solution of the problem of relaying is by no means easy, because of the very meagre forces at one's command and also on account of the complexity of the current to be relayed. However, a good deal has been done. I would like to mention something with regard to the work that has been done by Sir Oliver Lodge some ten or perhaps eleven years ago. Sir Oliver was one of the pioneers in this endeavour to magnify telephonic currents, and worked mainly with carbon, which at that time was almost the only material that seemed likely to prove successful, although a few other substances had also been tried. As a matter of fact, carbon, as the author has already mentioned, is, in its microphonic quality, excellent. If one draws what may be called the characteristic curve of a carbon microphone, that is to say, a curve representing the mechanical pressure on the contact and the corresponding current flowing, it will be found an excellent one, but curiously enough it is difficult to obtain. Some experiments were made ten years ago by Sir Oliver Lodge to show this. The difficulty with the characteristic curve exhibits well the erratic behaviour of the carbon microphone. If a carbon point be placed on an arm of the Kelvin balance and underneath another carbon fixed to the base, and then at the other end of the balance two coils be placed, one fixed to the arm and the other fixed to the base, one can in that way vary the pressure exerted on the carbon contact without disturbing the system, by simply varying the current flowing in the coils. With such apparatus one can draw the curve very nicely. As one gradually increases the current governing the pressure, the current through the contact increases, following a definite curve but, if one suddenly releases the pressure, the chances are that the original curve cannot be regained. I should like to ask the author whether he has obtained this curve for his relay. On the stability of the curve largely depends the success of the instrument. I should imagine from the mechanism of his apparatus that it ought to show an improvement on the carbon curve. Sir Oliver's main object was the reproduction of a monotone instrument. In this he was signally successful. He proceeded also to magnify speech, and some surprising results were obtained, but there was a loss in articulation which was rather serious. For instance, if two relays be joined in series the absence of the higher harmonics Mr. Davies.

Mr. Davies. in the second relay is very conspicuous. I should like to ask the author what were his results with regard to relays in series. Ten years ago it was thought that a good deal of this loss was due to the carbon itself, and not so much to excessive inertia in the apparatus. Things were strung up very tightly indeed ; the moving parts were made extremely rigid and very light, but in spite of that there was this loss, and it appeared to be mainly in the carbon itself. The power involving high frequency currents was frittered away, I suppose, through the want of elasticity, or in consequence of the vicosity of the material used. The hardness of materials is an important point in the author's relay. He has contact elements that are extremely hard. One would therefore expect better transmission of the harmonics of the voice in this case than with carbon, because on the relaying of those high frequencies depends the efficiency of the instrument from the articulation point of view. There is another point also. However perfect a relay may be, it can only relay what is given to it. I should like to ask the author if he has tried his relay on a really long line, because there is no getting over the loss in the line itself, that is to say, the loss of articulation due to distortion in its twofold aspect : that due to velocity differences and that due to real attenuation differences. One can deal with the cable ends in a small way and make things easy there, but in the body of the cable the conditions remain very bad. The cable interferes very much with the clearness of speech. This leads to another point which perhaps ought to be mentioned. Since we have now in Mr. Brown's relay a good instrument, an instrument which magnifies well, and, I suppose, articulates well too, it might be possible to work on distortionless lines, arranged for maximum articulation by the application of appropriate leakances and inductances.

I have brought one of Sir Oliver's instruments here for the inspection of members. It was designed some ten years ago, and Mr. Taylor, of the General Post Office, and myself have had some experience with it. The final design, as you see, is curious. Considerable difficulty was caused by extraneous noise, and to suppress the effects of noises the instrument was divested of all resounding areas. Any noise in the room would be picked up only too readily by this instrument if placed on any ordinary base. A base of wood, for instance, a foot square would be fatal to good working. That was one of the difficulties which had to be overcome. Another was mechanical tremor. That is, of course, serious in all microphonic work. There is, generally, a vast amount of tremor which has somehow to be suppressed. Tremor in this case was suppressed by suspending the relay from spiral springs. For that reason it was slung up in a special way, quite bare, with no resonating areas whatever to catch air waves. Once it was put up in this manner and boxed in, it worked very well indeed. The details of parts are these : The permanent steel magnet has an annular air-gap, in which is placed a little coil supported on a tuning fork, which is tuned to the sender. The coil at the apex of its support carries a small polished

carbon. The other carbon is secured to a very light reed. The reed is not tuned in any way, but is simply a body that has very much greater time of oscillation than the fork itself. This is damped by a little oil in the adjoining cup. The sender in one case was a tuning fork, specially designed to get over the difficulty of the variation of frequency with the pressure exerted by the little driving spring; that is to say, the mass of the fork was made very great, so that the little spring that kept it going should not interfere with the vibration in an appreciable degree. It is very surprising to find that about 1 watt will keep this massive fork vibrating. It gives about three hundred vibrations a second if I remember rightly. [Professor PERRY : Is the instrument for the transmission of one note ?] Yes, in this case. Sir Oliver also had an instrument for speech, but, as already pointed out, owing to the loss in articulation it was not so successful a relay as this. The instrument shown was particularly successful, for there was no difficulty at all about magnification, and articulation was not involved. [Professor PERRY : You mean by having more than one tuning fork ?] In that case it would not really be a tuning-fork instrument at all. The little coil would be suspended in a different way. In one case it was secured to a large sounding-board, which gave fairly successful results. With three magnifications the monotone instrument would give a note that would be audible outside this room, the original note being comfortably audible in a commercial 100-ohm Ader receiver. [Professor PERRY : But not speech ?] No, a monotone. Mr. Davies.

Dr. C. B. VOISEY : I have listened with great interest and attention to the description of the author's invention, the telephone relay, and though I cannot pretend to understand the technical details of its construction, I can appreciate and understand its application to the purposes of an extremely sensitive electrical stethoscope. I have had an opportunity of testing such a stethoscope in the ordinary way in a room in the out-patient's department of a hospital and over the telephone, and have been very much impressed by the loudness of the sounds. The fact that it has been possible to transmit the sounds of the heart with distinctness over long and short distances by telephone is sufficient evidence of its magnifying power. The ultimate practical value of the instrument is as yet difficult to predict; but one may speculate theoretically as to its possibilities, firstly from a physiological and secondly from a clinical point of view. To the physiologist it may be of great use in enabling him to demonstrate that what we now regard as primary sounds are in reality compound, and it may be a means of splitting them up into their constituents. It may also assist in enabling us to determine the exact relationship in time between the occurrence of the cardiac contraction and the cardiac sounds. At the present time they are regarded as synchronous; I think it is suspected that they are not actually so, but that the contraction precedes the sounds; we have no means as yet of determining this. Clinically it may be possible to detect sounds in the body which at present we suspect to exist but have been unable to hear owing to the fact that Dr. Voisey.

Dr. Voisey. our capacity has been limited to the sensitiveness of the ear itself. For instance, one might hear a sound caused by the friction of gallstones in the gall bladder or of calculi in the kidney. One might even hear the passage of the blood over the aorta which is rendered rough by disease. When this condition is exaggerated, it is possible to hear a sound now, but in the very early stages of disease it is not possible to do so. How far these theoretical ideas may be realised by the further development and perfecting of the electrical stethoscope it is yet difficult to say. There are many points requiring consideration. Loudness is not everything. It is necessary at the same time to have the means of choking down extraneous and adventitious sounds, and possibly, too, of tuning the instrument to different wave-lengths of sound so as to make it selective. I think that will be a difficult thing to do, but as the author has succeeded in solving so many difficult problems, he may be able to solve this one also.

Mr. Kingsbury. Mr. J. E. KINGSBURY: With regard to the million dollars reward offered for a telephone repeater to which the author refers early in the paper, I fear that competition in the construction of telephonic relays may be somewhat serious unless it be generally realised that that offer is not now open. It was made by a gentleman connected with one of the American telephone companies, but he retired from the telephone business some years ago. I think he has been connected since with the automobile, and also with the flying machine, business in which such sporting offers are somewhat more general, and have sometimes to be redeemed. With regard to the relay, I should like to fill up a part of the gap in the author's opening statement, for I do not think that he does complete justice to the workers in the intervening period. In 1905 there are patents (Nos. 9,605 and 9,606) standing in my name (but only as the representative of the owners) which describe a repeater which we called the Shreeve repeater, using the word "repeater" as they do in the United States, to represent "relay" as we use it here. That Shreeve repeater is unquestionably a practical telephone relay. Some five years ago I talked through it myself. I am sorry that I have no records that I can put before you, but I think that we should give Mr. Shreeve the credit for having solved the practical difficulty of a telephonic relay. There had been a demand for such a relay, as the author rightly says, from the very beginning. The first patent for a repeater was taken out by Gilliland. He received the patent in 1881, but applied for it in 1879, and he said then that there would be a demand for a repeater for telephones as there had been for repeaters in telegraphs. That is the case, but it is proved, as the author says, that the demand has not been filled in a way that we can regard as a complete, final, and satisfactory method for general adoption. The repeater which has been in use has been used, and is used, to a very practical extent, but I think I may say not largely. It is subject to drawbacks in the shape of adjustment which experience only will overcome, and which I feel sure that the author will himself tackle in the

same way. In making those remarks I wish at the same time to express my appreciation, and what I feel sure is the appreciation of all telephonists at the fact that another mind is brought to bear upon this subject, and also to express my anticipation of fruitful results as satisfactory, I hope, to the art as the author's previous essay which he put before the Institution, and equally satisfactory to himself. At the same time, one must realise that there are very important and difficult problems in this telephone relay. A relay which talks only one way is not a practical instrument; it must talk both ways. A telephonic conversation must be a conversation or it is not adapted to telephonic work. In the matter of construction the author has undoubtedly gone on new lines, but I wondered in looking over his description if those contacts of two metallic surfaces are not somewhat akin to the Berliner microphone. Of course, the automatic adjustment arrangement is entirely different from anything that Berliner ever thought about; there is an element in that of absolute newness, and I assume it must be of very great value. But although Berliner did not describe the operation of his microphone, I should like to know whether in fact his description of the two metallic surfaces in contact and the variation of the resistance by variation in the intimacy of contact was not in point of fact very nearly akin to the method which the author has adopted. The transmitter seems to me to be one of those promising fields of research and experiment upon which it is extremely satisfactory to have a new mind brought to bear. But I think the author may have been somewhat misled by the statements which he quotes from authorities in regard to carbon. I am very reluctant to question them, but my recollection is that carbon never was a substance that was controlled for telephonic purposes by patents. In England the control was effected by the Edison patent, which was simply the combination of a diaphragm with a tension regulator without regard to what constituted the tension regulator. As a matter of fact, carbon has invariably been used for telephonic purposes commercially, whether in countries where it has been patented or in countries where no patent protection could be obtained for it. That it is the best which has come before experimenters I take for granted by its continued use, but it cannot be the only substance which has been experimented with. My impression is that the Globe Company in London early in the career of the telephone made experiments with various substances. Perhaps Dr. Thompson will be familiar with them. But whether that be so or not, any further development in the invention of transmitters, whether it be in form or substance, cannot but result in untold good to the development of telephony. Mr. Kingsbury.

Mr. B. S. COHEN: It is to be hoped that the author will be enabled to devote the necessary time to perfecting this apparatus, as undoubtedly a considerable amount of work is still required to make both the relay and the transmitter of value for practical telephonic purposes. It would be interesting if he would explain a little more fully why he assumes that the action of the transmitter in the relay Mr. Cohen.

Mr. Cohen. is due to a stream of electrons passing between the contacts rather than to resistance variations caused either by variations in pressure, temperature, or surface of contact. Experiments were carried out in the National Telephone Company's Investigation Laboratory on the telephone relay and the metallic granule transmitter. Perhaps some particulars of these tests may be of interest. Considering the relay first, the results obtained were not quite so good as those given by the author in his paper, and this is very likely due to want of experience in adjusting the apparatus. However, considerable time was spent in adjustment to get as far as we could the best results. With one of the relays placed in the centre of a line the improvement with the relay was 19 miles standard cable, judging purely by volume. Articulation tests were then carried out. With 44 miles of cable in the relay circuit, and 25 miles without the relay, the number of words missed with the relay was found to be 55 per cent. more than without the relay. So that the articulation for equal volumes was about 55 per cent. worse with the relay. The balance of cables was now readjusted to give comparative lengths of audibility, with reference both to articulation and volume. The result was the relay gave a net improvement of 8 standard miles. Now, of course, that sounds very little, but it must be borne in mind that 8 miles of standard cable would represent approximately about 250 miles of trunk line. This improvement, as the author points out, would be considerably decreased if double repeaters working both ways were used. Mr. Kingsbury referred to the Shreeve repeater, and perhaps I may supplement what he said about this instrument by a few figures which have been kindly given me by the Western Electric Company. This instrument is in use by the American Telegraph and Telephone Company in the United States on a number of long lines. The repeater is generally used in series in the middle of a line whose total length is not less than about 12 standard miles. On a less length than this trouble is experienced by reason of the instrument singing. To get the best results, the repeater must be at the exact electrical centre of the line so that the lines on each side of the repeater balance. Under these conditions the articulation is very good. The improvement under these conditions, using double repeaters working both ways, is about 6 standard miles. More than one repeater can be inserted in the line. For example, on one of the long lines running out of Boston 1,500 miles long, three repeaters are joined in series, giving a net improvement of 18 standard miles. A number of tests have been carried out with the author's metallic granule transmitter, and the results obtained with this are decidedly encouraging. Under favourable conditions the transmitter gave an improvement over the commercial common battery transmitter with carbon granules of 10 standard miles, and the articulation was as good. It will be realised from these figures that the transmitter is quite promising provided that the commercial product could be turned out in bulk with the same efficiency. Unfortunately, I believe the author has been unable

to design an instrument of this type capable of working on the standard common battery circuits. This limits its usefulness. It is to be hoped that he will be able to overcome this difficulty. Mr. Cohen.

Mr. A. C. BOOTH: It has been my privilege to experiment with Mr. Brown's relay at intervals during the last three months. It was first tried for intensifying the received signals at radio-telegraph stations, and gave very promising results, magnifying the received signals from four to twelve times. It has also been tried for working as a repeater for telephone purposes, that is, it was placed in the middle of an artificial telephone line of 68 miles of standard cable, the type of cable to which the author refers, with the result that the speech at the end of this line was very little inferior to that of the 34 miles of standard cable without the relay. Of course that was a line under ideal conditions. When the line was put direct through 68 miles, speech was practically nil. As a further test, the relay was placed half-way along 108 miles of standard cable, and although conversation was out of the question, one could clearly distinguish that speech was being made, whereas without the instrument the 108 miles of cable was absolutely silent. We have only just commenced the stage of actual trunk-line working. Having dealt with the practical advantages of the instrument, I must now refer to its weaknesses, though I do so in no spirit of injurious criticism. In the first place, although the adjustment is simple, it has been my experience that the instrument takes time to settle down to its work. Sometimes more than an hour has been spent continually regulating before good results could be obtained. That, of course, may be due to insufficient experience on my part. Secondly, in regard to radiotelegraphy, the detectors are as a rule absolutely dead silent except when signals are being received, whereas the relay gives a very slight but appreciable noise, due to its microphonic qualities. This noise is not the whistling or humming that arises with a too sensitive adjustment. Although so small, it seems to have a disturbing effect on the operators, who, it must be remembered, have to wear headgear telephones for several consecutive hours daily. As regards trunk telephone circuits, it is obvious that such a very sensitive instrument will magnify any defects or disturbances that may exist upon a line; and, as a rule, the longer the line the greater the number of minor defects, and it is on the long lines that such an instrument will be used. Then, as regards the to-and-fro conversation, the switching necessary for this is certainly a disadvantage, and if the public are paying 10s. for 3 minutes, I am afraid the switching operations will appear to occupy more time than the conversation. The instrument has not been in use sufficiently long to give any idea as to its stability under continuous working conditions, and I fancy that some slight re-regulation will occasionally be necessary. This, of course, is another weakness, as the telephone public expect perfect speech with no lost time, quite irrespective of the length of line employed. Mr. Booth.

Dr. W. H. ECCLES: I wish to speak not on the general problem of Dr. Eccles.

Dr. Eccles. telephone practice but on the narrow issue of the application of the telephone relay to wireless telegraphy. It has always been my experience with such relays that if they are not monotonic, not acoustically selective, they magnify atmospheric and other sounds as well as the signals from the proper sending station. This last year I have been working on a relay tending to be selective. In fact, if in the author's relay we substitute an iron wire for a reed, and stretch the wire so as to be at a frequency equal to that of the singing notes that are used in modern wireless telegraphy, and regulate the gap in the same way as he regulates it, it will be exactly the relay I have brought here with me to-night. It is in a very crude state, and not fit to be shown, but any one who will examine it will see that it is based on almost the same principles as the author's, except that instead of a damped reed I use a free wire. Now one difficulty I have found with this selective form of relay is that it does not select so well as is necessary. When a stretched wire is put very near to a point in oil you get such considerable damping that the possibility of getting perfect selectiveness is much reduced. One speaker this evening asked for a selective relay. I think this is one of the chief objections against good selectivity. I have usually worked with this relay on the Clifden signals as heard in London up to last December. They are very faint indeed, and although I could get them magnified about two or three times, I found that one of the vices of the instrument was that it sometimes started singing on its own account and went on singing for 5 or 10 minutes. The only other points I need raise here are with regard to the theory of the instrument. The author refers on page 591 to the theory of gases and the passage of ions through the air across the very narrow gap, and then later in the paper he proposes to put oil there and get rid of the air. I agree with Mr. Cohen's supposition that a main point in the explanation of the action of this relay is that the resistance of a thin film of oil is varied by the variation of its thickness when the diaphragm of reed or wire moves. If x be the thickness of the air or oil film at the contact, $x \rho_1$ its electrical resistance, R the resistance of the regulating coil, and a the film thickness in the undisturbed position of the wire, the restoring force on the wire is given by—

$$F \propto x - a - \left(\frac{b}{R + x\rho_1} + c\right)^2,$$

where b and c are constants governed by the E.M.F.'s employed. Therefore in the equilibrium position—

$$\frac{dF}{dx} \propto 1 + 2 b \rho_1 \frac{\sqrt{x-a}}{(R + x\rho_1)^2},$$

showing that the equilibrium is remarkably stable. Taking that, we can get a good idea of the size of the gap that is maintained by this automatic regulation devised by the author. Some years ago Dr. P. E. Shaw proved by the method of electrical touch that the

minimum audible sound involved a diaphragm movement of 0·7 of a millimicron, that is to say, 0·028 of a millionth of an inch. By the same method Dr. Shaw measured displacements as small as 0·016 millionth, which proved the possibility of relaying inaudible motions. Taking this movement as causing about one-half of 1 per cent. variation of the film thickness, it suggests that the conduction space in Mr. Brown's instrument is about 4 millionths of an inch, which is about the length of a chain of 100 molecules according to Kelvin's estimate. Compare this with a wave-length of blue light which is 12 millionths of an inch, and we see the delicacy of the automatic adjustment in Mr. Brown's instrument. I myself, as also another experimenter with my own crude instrument, did not succeed in making the instrument reliable, and may therefore the more warmly congratulate Mr. Brown on his achievement. Dr. Eccles

Mr. E. H. RAYNER: First, I would like to ask the author if it is necessary to have the point of negative polarity as shown on the sketch, or if it may be positive. [Mr. BROWN: It is advisable to have it negative. It is much better.] Can you give us any reason for it? [Mr. BROWN: I think it is for the same reason that the small carbon in an arc lamp is made negative. There is no question about the ions. The ions flow better to a sharp point.] There is one other point. You mentioned the use of "invar" for the reed only. Is that for magnetic purposes or mechanical purposes, or do you think it would be an improvement to make a greater use of "invar" to keep the dimensions constant and avoid temperature changes? [Mr. BROWN: It is for keeping the dimensions more constant and to keep the reed from warping.] The other parts of the instrument might equally cause trouble from alteration of dimensions. [Mr. BROWN: It was used simply because it was thought that the reed was likely to buckle under the effects of temperature, because with "invar" there is no coefficient of expansion. That stops it entirely. It might be better if the whole instrument had been made of "invar," but we have not got to that point yet.] Mr. Rayner.

Mr. D. H. KENNEDY: The paper deals with three subjects, but I think it is safe to say that the telephone relay is the subject which telephone men have turned to with the greatest amount of interest. Personally I feel intensely interested in the practical aspect of the question. After reading the paper I endeavoured to relapse into the sceptical attitude, which is born of long aquaintance with this unsolved problem, but knowing what I did of the author and his achievements I found it somewhat difficult. The reading of the paper was, of course, sufficient to let me see that he had broken entirely new ground. On the following morning I was invited by Mr. Booth to listen to his tests, and I will relate my experience as simply as I can. I walked into the telephone test-room and sat down in the operating chair. Mr. Booth gave me the receiver, and I heard a distant voice which said, "1, 2, 3, 4, 5, A." Mr. Booth turned a switch and then the voice said, "1, 2, 3, 4, 5, B." This operation was repeated three or four Mr. Kennedy.

Mr. Kennedy.

times. Then Mr. Booth said to me, "Which is the better?" and I said, "'A' is the louder; 'B' is the better articulation." He said, "'A' is with the telephone relay in the middle of 68 miles; 'B' is 34 miles." So, in my opinion, the telephone relay gave a little greater audibility through 68 miles than was obtained direct through 34 miles without it. There was a little difference in the quality, but not more than one is accustomed to find in changing from one transmitter to another. Subsequently I listened to the same voice speaking through 108 miles of standard cable with the relay at the centre, and I was able to follow what was being said. When the relay was cut out, the cable, as Mr. Booth said, was quite dead. In the afternoon I returned to the same room; a Glasgow trunk had been taken and the relay was connected to the end of it. On the question of adjustment I may say here that I arrived at the room before Mr. Booth and I put the instrument slightly out of adjustment. I did not treat it in a very gingerly fashion, but I found no difficulty whatever in getting it back into adjustment, and I was very much struck indeed with the wonderful way in which the milliampere-meter needle followed the movement of my hand on the adjusting screw. It seemed to be quite possible to increase the current milliampere by milliampere. Then I listened to the man speaking from Glasgow. There was an increase in audibility, but unfortunately there was also a great increase in the extraneous noises, and that, of course, is one of the lions in the path of the author. It is however, quite possible, to think of the instrument being used under conditions where these extraneous noises will not be present, as for instance in connection with submarine cables, and then indeed the value of the instrument must be very great. With regard to the difficulty of reversing, I do not know whether the author has considered the advisability of using the instrument pretty much in the same way as we use a telegraph relay—in the local circuit at each terminal station—with a hand-switch in the receiver so that it could be cut out when speaking and left in when listening. That seems to me to be perfectly practicable, though other people think differently. One point of criticism occurs to me: Where is the oscillograph? I did expect we should see some oscillograms showing the performances of the instrument. No doubt they will come along later. Again, on the question of carbon, the paper says that "a material is wanted that will not only conduct well but change its resistance to pressure more readily than carbon." I thought it had been definitely established that carbon does not change its resistance under pressure, and that the microphonic phenomenon is one which depends upon greater or less intimacy of contact between the particles. It may be that I am of a sanguine temperament, but I think that this instrument, when brought into practical use, will greatly increase the distance over which speech will be possible.

Mr. Mordey.

Mr. W. M. MORDEY: May I bring the members back a little to the early days of the telephone and the microphone? When I heard the discussion turn on the question of carbon or metals, I

remembered that several papers were read and discussed here a good many years ago on that subject. I will read a few lines from the discussion on a paper on "New Telephone Transmitters" by John Munro.* Professor Hughes (who was President in 1886), the inventor of the microphone, speaking on the question of carbon and of metals, which was then under discussion, said: "The point brought up to-night by Mr. Munro is one which I tried to point out in my first paper, namely, that by means of a number of metal contacts we could transmit speech just as well as by carbon. I remember showing at Mr. Preece's house before I brought the patent out, and I think he was very much astonished at it, that if several nails were placed together and spoken to they would transmit the voice, and that I think was the first metal microphone Mr. Preece had seen." Going back to the paper itself, I find on page 130 the following: "The carbon microphone is now shown to be only one illustration of Professor Hughes' wide discovery that a delicate contact between any two conductors has the property of transmitting sounds. The Reis original transmitter, with a delicate platinum joint, is seen to have been another illustration of the same phenomenon. Professor Silvanus Thompson has recently presented proof that Reis did send articulate words by his transmitter; and I believe there is no doubt he did. I have myself heard by telephone, and understood, single words spoken direct to the platinum contact of a Reis transmitter. Reis, then, employed a platinum microphone, without knowing it, as early as 1861; and Edison used a carbon microphone, without knowing it, in 1877. The discovery of Professor Hughes, in 1878, threw a flood of light on both inventions." Mr. Mordey.

I am sure it would interest members to read the early discussions on this subject. In this one volume there is other valuable matter on the subject, including a paper by Shelford Bidwell, whom we have recently lost, on "Microphonic Contacts," one by Probert and Soward on "The Influence of Surface-condensed Gas on the Action of the Microphone," one by W. Moon "On a Static Induction Telephone," and a mass of interesting matter contributed by speakers in the discussions.† I do not bring this up to lessen the credit due to the author for what I consider is a very real and substantial advance in telephony, but to remove any impression that there is anything new in using metal for microphonic purposes. That was one of the first things tried. I remember very well seeing Professor Hughes demonstrate microphonic action with three French nails at one of our meetings.

Professor JOHN PERRY: It is of much importance that the members should hear the great leaders of the telephone industry, and I will, therefore, communicate my remarks later. One word, however, about the adjustment. I am afraid that the speaker who referred to the subject has been a little unlucky in the instrument he tried. I have seen a young lady adjust an instrument several times quite quickly and without any difficulty, and if I remember rightly, I was told by her Professor Perry.

* *Journal of the Institution of Electrical Engineers*, vol. xii., p. 137, 1883.
† Ibid., vol. xii. pp. 173, 205, 251.

Professor Perry.

that it kept in perfect adjustment for twenty-four hours. All the phenomena depend on the variations taking place in this little space which is only a few millionths of an inch in thickness, and yet the instrument may be turned upside down and get rough treatment without getting out of order.

Communicated: Some twelve years ago Mr. Brown was a young engineer employed in designing electrical machines. He saw that many clever young men were doing this kind of work, so he studied submarine telegraphy, which was a neglected subject. As a result he invented the submarine telegraph relay described in his paper before the Institution,* used now by practically all the cable companies of the world. There are three marvellous inventions in that contrivance to which I constantly direct my students' attention because of their individual importance in mechanical and electrical science. To-night we have another epoch-making invention from him. He has described its use for some medical purposes and for the use of deaf people, but its most important immediately successful use is in wireless telegraphy, which it makes possible for enormous distances. Our chairman and another speaker accentuate the fact that this instrument is like a microscope, it magnifies the currents received by it, and as telephonic currents after a long journey are rather demoralised there may not be much use in magnifying them. But I beg to point out that at last (after twenty years delay) the discoveries of Heaviside are being utilised; on the very day after this paper was read, the first "Heavisided" cable was laid across the English Channel. If Heaviside is followed, telephonic currents after long journeys may be very weak, but they will be undistorted, and mere magnification is all that they will need. It is no great draft on our intelligence to believe that this relay will enable good speech to be transmitted by cables and overhead wires between any two places in the world. The author has pointed out that just as carbon, so well established as the best material for lamps, has now given place to metal, so carbon is to be displaced by metal for use in microphones. I wish that young engineers would learn the general lesson which this teaches. Elaborate measurements are made at the starting of a new department of engineering; certain rules are established, and all engineers for many years use these rules making no further experiments, making no effort to study fundamental principles; then after long years somebody resuscitates old ideas which had been relegated to the scrap-heap, clears his mind of all common formulæ and methods, and revolutionises the practice of the profession. Dr. Lodge mentions viscosity as the defect of carbon for microphone work, but I know that years ago Mr Brown was able to state clearly what were the qualities wanted in the material. As he put it to me, he was looking for a material not only hard, infusible, and conducting, but also as elastic as the best cold steel even when raised to a white heat. He saw that if he wanted considerable current, if this current had to pass through material of small section, the rise of tempe-

* *Journal of the Institution of Electrical Engineers*, vol. 31, p 1060, 1902.

Professor Perry.

rature became a serious thing. He knew exactly what he wanted, and after a diligent search he has now found the substance in the alloy of osmium-iridium when the commercial variety of that material is treated in a particular way.

But this was not enough; he was not satisfied with our ordinary vague notion of a contact; he studied the phenomena occurring in a space bounded by two surfaces of metal, of a thickness of a few millionths of an inch. J. J. Thomson and others have shown that the electrical resistance of such a space is exactly proportional to its thickness. If, then, c be the current to be magnified, the change of thickness must be proportional to c; that is, the thickness is to be a constant amount together with a small varying amount. But the constant amount being very small, and indeed the varying amount also, they would certainly alter with changes of temperature, motion of the instrument, etc., and he has invented a method of making the action practically independent of such changes. Some of the speakers have said that they had difficulty in adjusting the instrument; they must have been using very antiquated forms, for the adjustment is a matter of certainty and takes only a few minutes; readjustment is not needed during a whole day, and during that day the instrument may be repeatedly turned upside down and jolted. The author says in his paper that the current regulates the state of the contact much in the same way as the current through the arc lamp maintains the length of the arc. There can be no doubt of the existence of a wonderful self-adjustment, but in view of the interesting facts given by the author in his appendix, I do not think that the action of the instrument is very clear. I have not had an opportunity of verifying the following theory by actual experiment, but it may be worth while to give it. There can be no great error in neglecting the back E.M.F. due to motion of the telephone disc or the inertia of the reed or in assuming that the variable part of the current through the telephone is small compared with the steady current. The varying current c through H (Fig. 3 of the paper) is to be faithfully copied and magnified, becoming C in the local circuit. The total current through the local circuit consists of the variable part C and a constant part C_0; the total $C_0 + C$ I shall call γ. The attracting field, which acts on the reed P, tending to increase the resistance of the local circuit, is partly constant and partly due to n turns of c and N turns of γ. In the local circuit, if E be the E.M.F. of the battery, the resistance will consist of two parts; first, that of the battery, etc., the impedance of the telephone, and that part of the contact resistance which does not depend upon the field or currents altogether $R_0 + L\,\theta$ (where θ stands for d/dt); secondly, the increase of the contact resistance which is proportional to the field, that is, to $n\,c + N\,\gamma$ where n and N are numbers of turns. The contact resistance is diminished by electrostatic attraction, and it is easy to show that this is proportional to γ^2. The total resistance is then $R = R_0 + L\,\theta + a\,(n\,c + N\,j^2) - g\,\gamma^2$ where a and g are constants. Again, as the magnet is a transformer—

$$Rj + k\,n\,\theta\,(n\,c + N\,\gamma) = E$$

Professor Perry.

when k is a constant. Substituting, and in simplifying, neglecting the squares, etc., of C, we have—

$$R_0 C_0 + a N C_0^2 - g C_0^3 = E,$$

and—

$$C = (a C_0 + k n \theta) n c \div \{R_0 + 2 a N C_0 - 3 g C_0^2 + (L + k N n) \theta\}.$$

I have had no opportunity of verifying this theory by experiment, so I must leave it at present. It is, however, worth while to show how the working of the instrument is not upset by quite large changes in ρ, that part of the constant resistance which depends on mere adjustment, that is which does not depend upon the magnetic field or electrostatic attraction. As this is only a rough application of the theory I will neglect the electrostatic attraction, that is, I will take $g = 0$; also I will take $k = 0$, so that I neglect the small electromotive force in the local circuit due to the fact that the magnet is a transformer, and thus we have—

$$C_0 = E/(R_0 + a N C_0) \text{ and } -C = \frac{a n C_0 C}{R_0 + 2 a N C_0 + L \theta}.$$

Theory shows that there is an interesting compromise in Mr. Brown's statement that the best adjustment is to halve the maximum steady current, that is, to let $a N C_0 = R_0$. Thus if the telephone and everything but the contact have a resistance of 40 ohms, and if the independent contact resistance ρ is adjusted to 70 ohms so that $R_0 = 110$, then if E is 300, C_0 is 1. I am not now troubling about the units of E and C_0. Assume the extra impedance of the transformer due to varying currents to be 40 ohms, let $a n$ be 9,800, and we have $C = 20 c$. Now by turning the instrument upside down or by other violent treatment or bad readjustment suppose we alter ρ to 118 or to 28, let us calculate the effect. I take $C = b c$—

ρ	118	70	28
$R_0 + L \theta$	198	150	108
C_0	0·90	1·00	1·10
b	19	20	20·7

These are very great disturbances of the contact, and yet we see that they do not greatly affect the constant b.

Major O'Meara.

Major W. A. J. O'MEARA, C.M.G. (*communicated*): I was recently at Bolt Head wireless station and I was surprised at the intensity of the signals which were received when Mr. Brown's relay was being used there, and such disadvantages as the relay may possess do not operate so seriously in radio-telegraphic working as they might in trunk telephone working. Telephone engineers have for a long time been

Major O'Meara.

desirous of obtaining an efficient telephone repeater, and whilst I was in America recently I was glad to note the improvement which had been made in these instruments and the results which were being obtained by their use. The British public, however, is severely critical in telephone matters, and I am afraid that it would not accept Mr. Brown's telephone relay in its present stage of development on account of certain unavoidable limitations connected with it. The principal objection would be the switching to and fro of the relay as conversation changed from one direction to the other. We cannot fail to recognise the valuable work which Mr. Brown is performing, but as in the case of every instrument which marks an advance in a new direction it still has its weaknesses, and it remains to be seen by practical trial whether the advantages which may be derived from its use outweigh the disadvantages.

The Chairman.

The CHAIRMAN: In the course of a most interesting discussion we have heard a great deal about what the author speaks of as a relay and what some speakers have called a repeater. Before calling on the author to reply, I wish to draw your attention to the fact that not only is Mr. Brown's "relay" not, strictly speaking, a relay, but that no complete telephone relay has ever been invented, nor has any approach to one been made. The origin of all relays was a fresh horse *released* from the stable (old French, *relais* = release). In the old days when people travelled, instead of being projected as they are nowadays, they used to travel very comfortably on horseback, and when a man's horse got tired he went to the nearest posting house and got a fresh horse, which he called a relay, and went off on it. That is to say, he started again like a new man on a new horse just as he had done at the beginning of his journey. When telegraphy came in some one invented an instrument which actually enabled the feeble currents which arrived at the far end of the line to be restarted, or rather new currents to be started, precisely the same in shape, in number, in frequency, and in duration, as those which were sent out at the original sending station. That instrument was quite legitimately called a relay. But when we come to telephony the problem is totally different. Telephonic speech currents are most easily thought of as a large number of separate alternating currents of different frequencies and different amplitudes. They all start out with the right phase relations, the right proportionate amplitudes, and the right frequencies for articulate speech, but when they arrive at the far end of a cable or long telephone line, their amplitudes have fallen off, the different frequencies falling off in different degrees. The consequence is that the proportion between their amplitudes is all wrong. Moreover, the shape of the received waves and their phase relations are all wrong. Now a complete telephone relay must not only restore the amplitude, which is what Mr. Brown's relay does, but it must restore the different waves to the same phase relationships, the same amplitudes, and the same shapes as they were when they started. I am not at all sure that that is not an impossible problem to solve, but I should not like to assert definitely

The Chairman. that it is impossible. One would have said off-hand that it was quite impossible to know what the stars are made of, yet we do know. I have been very much struck with the possibilities of the author's repeater or relay for wireless telegraphy. It seems to me to be the most marvellously sensitive detector and magnifier of electric currents that has ever been devised, and I see no end to the possibilities of its use for magnifying currents. For that is what it really is, it is not a relay in the strict meaning of the word: it is a magnifier.

Mr. Brown. Mr. S. G. BROWN (*in reply*): I shall endeavour to answer the questions asked by the following general statements: It was found from experience best to make the lower contact flat and the upper one pointed, perhaps because there was less damping produced in the oil by the upper point. The contact-pieces should be carefully chosen by testing them in the relay itself, and, if the contact produces of its own accord bubbling and squeaking noises, the contact-pieces should be discarded and replaced by others until a quiet microphone is obtained. With the majority of contacts, when they are very sensitively adjusted, a faint continuous sound can just be noticed in the telephone; this is usually of no moment, except perhaps when the relay is required to work at the extreme limit of audibility. It is possible by testing a number of contact-pieces to obtain several that will form microphones, which, when delicately adjusted, will be absolutely dead silent except when signals are received. The best contact-pieces are the hardest, and the majority of them will turn the edge of the hardest file. As regards the articulation of the relay, this can be made very good if the reed upon which the lower contact is mounted is constructed of hardened and tempered tool steel, and for this reason I have abandoned the use of the soft "invar" steel. A good test for clearness of speech is to telephone from one room to another, using a Bell receiver as a transmitter; now introduce the relay, and it will be found that in spite of the increased volume of sound the articulation is as good as before. Some have pointed out that however good a relay may be, it would be useless to apply it at the ends of a long line, because of the distortion of the speech produced by the line itself. In answer to this objection I would say that a relay may be placed in the middle of a long telephone cable, and far better speech be received than at first sight it would appear possible to obtain. A relay by resonating somewhat to the shrill upper notes and being less sensitive to the lower ones, may do a great deal of correction without additional assistance; but by using series capacity and leaking inductance of suitable values at the ends of the lines distortion may again be greatly reduced. I placed the problem before Professor Perry, and he calculated that by using the capacity and inductance at the ends of, say, 60 miles of standard cable, the distortion and alteration of phase may be considerably minimised. In fact, by placing such devices, say, every 10 miles, perfect clearness of speech may be produced throughout the whole cable, the attenuation remaining being corrected by the relay. I have worked two telephone relays in series only on one

Mr. Brown.

or two occasions; the increased magnification is enormous and requires skilful handling, and the articulation is fairly good. A relay may be made monotonic or resonate to one particular note by arranging the natural period of the reed to coincide with the note desired and by reducing the damping, say, by fixing the reed further away from the magnet. The damping produced by the oil on the contact may be made very small by using only a trace of oil and by keeping the upper contact sharply pointed.

The Chairman.

The CHAIRMAN: I will now ask you to pass a hearty vote of thanks to Mr. Brown.

The vote of thanks was carried by acclamation.

STANDARDISATION OF FUSES.

By H. W. KEFFORD, Associate Member.

(*Paper received March 22, and read at Birmingham on May 25, 1910.*)

The standardisation of electric fuses and the enforcement of more stringent regulations with regard to their design and use would contribute greatly to the increased safety of electrical installations and would put the manufacture of this class of apparatus on a more uniform and scientific basis. So long ago as 1905 an editorial in one of our electrical journals* drew attention to the importance of standardising low-tension fuses, and, whilst regretting that we lagged far behind other countries in giving this matter the attention it deserved, took comfort in the assurance that, at some future date, we should fall into line. The difficulties to be overcome before a standard system of fuses can be brought into general use are certainly numerous, but delay renders the problem more and more complex. The necessity for and advantages of standardisation do not require very much demonstration, and the only point in this connection which the author desires to emphasise is the importance of simplicity, efficiency, and reliability in every detail of the electric circuit. If we would foster the popularity of electrical applications and the prosperity of the industry we must create and maintain confidence in the safety, reliability, and convenience of electrical power by every possible means. In addition to contributing largely to the attainment of this end the standardisation of fuse design would undoubtedly conduce to economy in manufacture and result finally in a reduction of cost.

Makers of fuses now display in their catalogues so many types and so many designs of each type that it is difficult to escape the conclusion that the fuses are ornamental adjuncts to a switchboard and may be chosen in a style most suitable to, say, the scrollwork which supports the clock. Up to a certain point it is a very simple matter to determine the behaviour of a fuse when blown under working conditions, and this fact renders still more inexplicable the retention of many types which are wholly inadequate and of others which are needlessly elaborate.

In the present paper the subject is dealt with from a practical rather than academic point of view, the object being, if possible, to suggest a few lines along which certain essential questions may be

* *Electrical Review*, vol. 56, p. 713.

tackled. The results of tests on commercial fuses will be considered in conjunction with corresponding theoretical indications, and definite deductions will be drawn as to the most suitable quantitative and structural properties for a standard line of fuses. Up to the present time the tests referred to have been confined to low-tension fuses up to a normal carrying capacity of about 60 amperes, but it is hoped to continue the experiments on fuses of much larger capacity.

The complete specification of a line of fuses will embrace :—

(*a*) A definition of the "marked" or "rated" current in terms of the "limiting" current (also called the "normal fusing" current).
(*b*) A standard range of rated-current values and voltages.
(*c*) A definition of one or more points on the "time-overload" curve of each fuse.
(*d*) Regulations as to non-interchangeability, temperature rise, freedom from deterioration, and perfect operation under all conditions.
(*e*) Specifications for the standard method of carrying out short circuit, temperature rise, and overload tests.

In framing suggestions with regard to the above points due consideration is demanded for the user, the workman, the retailer, and the manufacturer; for example, the quantitative properties of the fuses should lend themselves to simple control in the factory, the number of types should be reduced to a minimum, the price should be moderate, etc.

(*a*) The Rated Current.

As is well known, the chief characteristic of a fuse for quantitative purposes is its "time-overload" curve and the asymptotic current value of this curve to which the name "normal fusing current" has been given, but which will be referred to in this paper as the "limiting current." Fig. 1 shows the general type of a time-overload curve, of which the abscissæ represent the time intervals from the moment of switching on, and the ordinates either amperes or percentage overload above the rated current. The curve is asymptotic to the ordinate A B, and the current value corresponding to this asymptote is the "limiting current." The strict definition of the limiting current is the minimum steady current which will produce fusion after an infinite time interval, but for practical purposes we might substitute with advantage a definition referring to a definite time-interval—say 4 hours—instead of the unlimited period. The limiting current or limiting overload is the one fundamental quantity to which any definition of rated current should refer. An appropriate way of defining the rated or marked current of the fuse is as follows: A fuse which is rated at R amperes must fuse within 4 hours when carrying a times its rated current, but must be capable of carrying $a - \alpha$ times its rated current for at least 4 hours

without fusing. If L amperes is the limiting current, the rated current R amperes must lie between $\frac{L}{a}$ and $\frac{L}{a - \alpha}$.

The values chosen for a and $a - \alpha$ depend on a large number of practical considerations, and should also be selected with a view to facilitating the application of the above definition in factory and test-house. Thus the difference α between the two values may be looked

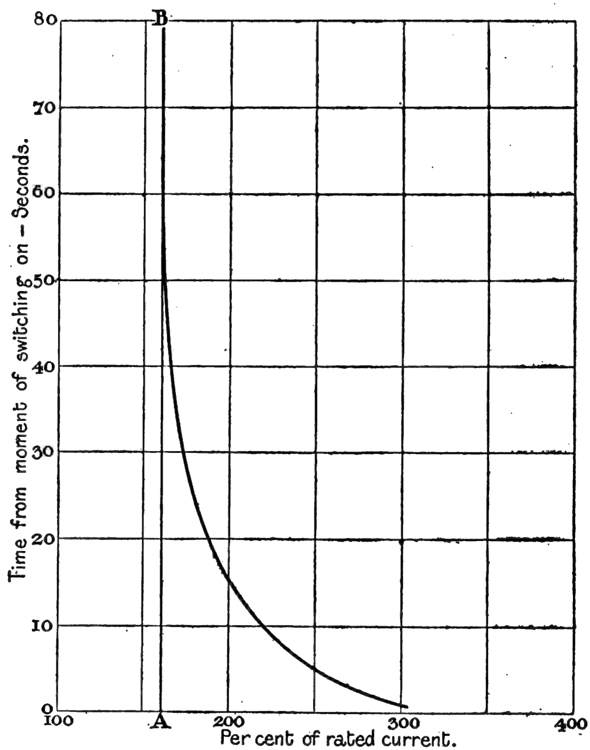

FIG. 1.—General Type of "Time-overload" Characteristic of a Fuse.

upon as a measure of the accuracy with which the specified conditions can be attained in manufacture.

The latter point recalls the fact that the Wiring Rules of this Institution require that no fuse shall carry more than 200 per cent. overload without fusing (*i.e.*, $a = 3{\cdot}0$), whereas the rules of another recognised authority in this country restrict the permissible overload to 50 per cent. ($a = 1{\cdot}5$). The writer has recently heard of suggested modifications to the overload regulation from two independent sources, one of which was a proposal to permit an overload of 300 per cent.

($a = 4$), while the second authority was of the opinion that the permissible overload should be even less than 50 per cent. if manufacturers could work to a narrower limit. If, as may be assumed, the smaller overload is the one dictated by considerations of safety, irrespective of manufacturing limitations, whereas the higher figure is based on a compromise between what is desirable and what is present

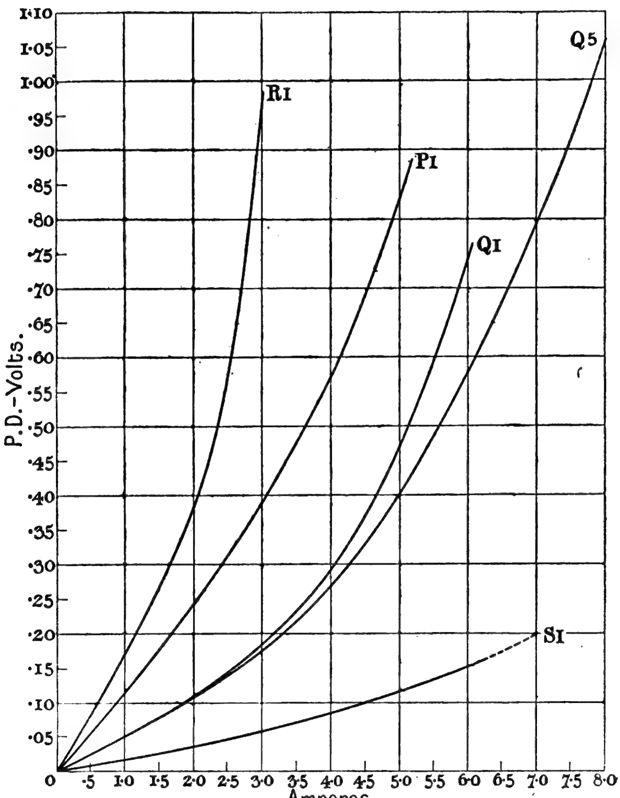

FIG. 2.—Pressure Drop across Fuses Rated at 4 Amperes.

practice, these figures furnish one of the most striking arguments for the need of a system of non-interchangeability for fuses of small capacity. This point will be dealt with more fully later in the paper. The regulations for enclosed fuses by the Underwriters Association in the United States, which have been framed with the co-operation of manufacturers, fix the values of a and $a - \alpha$ at 1·25 and 1·10 respectively, but these figures were only decided upon after manufacturers had endeavoured to work to a smaller value of α than 0·15, as

specified above. These close limits are in marked contrast with the figures quoted above.

The results of an experimental investigation of the properties of current commercial types of fuse should give a reliable and useful indication of the possible values of a and $a - a$, the limits between which the ratio $\frac{\text{limiting current}}{\text{rated current}}$ must lie, and it becomes a relatively simple matter to determine whether this ratio should have

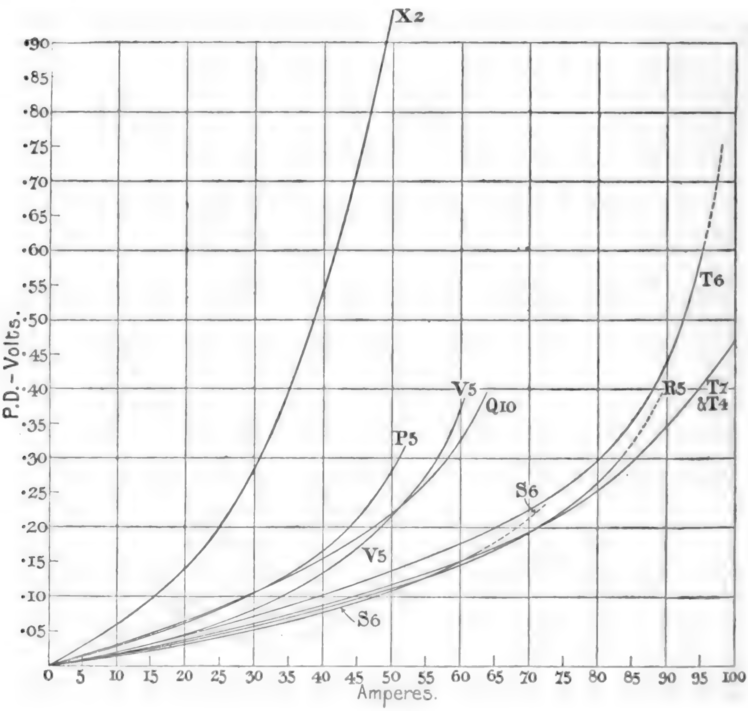

FIG. 3.—Pressure Drop across Fuses Rated at 50 Amperes.

the order 4 or 1·5. In drawing inferences from such tests due weight must be given to the many other properties which are closely connected with the ratio a, and observations must be made of running temperature, voltage drop, behaviour when blowing on overload and short circuit, and general reliability and safety.

Table I. is a summary of some of the tests carried out on a representative variety of fuses in common use; illustrations of a few of the fuses tested are shown in Plate I. A distinctive letter has been given to all fuses made or supplied by one firm and the various sizes and types are denoted by a number which follows this letter. Figs. 2 and 3

TABLE I.

Symbol of Fuse.	Rated Current.	Rated Maximum Voltage.	Ratio. $\frac{\text{Limiting Current}}{\text{Rated Current}}$ $a - a$ Minimum.	Ratio. $\frac{\text{Limiting Current}}{\text{Rated Current}}$ a Maximum.	Voltage Drop at Rated Current.	Voltage Drop at Rated Current $\times\, a - a$.	Watts Lost at Rated Current.	Watts Lost at Rated Current $\times\, a - a$.	Remarks.
P_1	4	500	1·25	1·50	0·572	0·830	2·290	4·15	
P_2	10	500	1·30	1·40	0·247	0·351	2·470	4·21	
P_3	20	500	1·58	—	—	—	—	—	
P_4	30	500	0·93	1·07	0·300	0·235	9·000	6·58	
P_5	50	500	1·00	1·16	0·277	0·277	13·870	13·87	
Q_1	4	250	1·63	1·75	0·288	0·740	1·150	4·44	
Q_2	6	250	1·67	2·00	0·232	0·695	1·390	6·95	
Q_3	10	250	1·50	1·70	0·143	0·263	1·430	3·68	
Q_4	15	250	1·53	1·67	0·151	0·306	2·120	6·11	
Q_5	4	500	2·00	2·25	0·268	1·060	1·070	8·48	
Q_6	6	500	1·50	1·67	0·315	0·600	1·890	4·80	
Q_7	10	500	1·70	2·00	0·161	0·529	1·610	9·00	
Q_8	15	500	2·00	2·20	0·149	0·484	2·080	14·52	
Q_9	30	500	1·27	1·43	0·255	0·484	7·140	18·36	
Q_{10}	50	500	1·40	1·60	0·224	0·321	11·200	19·26	
R_1	4	550	0·75	1·00	—	0·958	—	2·87	Dangerous on short-circuit. Case burnt on continuous overload in all fuses. Calibration very ununiform.
R_2	10	550	0·80	1·00	—	0·272	—	1·91	
R_3	20	550	1·38	—	—	—	—	—	
R_4	30	550	1·07	1·27	0·235	0·387	6·580	12·07	
R_5	50	550	1·60	1·70	0·111	0·265	5·560	21·21	
S_1	4	250	1·50	1·75	0·082	0·153	0·328	8·20	Case burst on all short-circuit tests of these fuses and frequently on overload tests.
S_2	10	250	1·00	1·20	0·180	0·890	1·800	10·66	
S_3	10	500	1·15	1·20	0·203	0·983	2·030	11·79	
S_4	20	500	1·98	—	—	—	—	—	
S_5	30	500	1·27	1·40	0·106	0·412	2·970	15·66	
S_6	50	500	1·40	1·60	0·109	0·151	5·450	9·06	
T_1	6	250	2·67	3·00	0·078	0·563	0·466	9·01	All these fuses behaved irregularly on overload, and a continuous arc was often formed.
T_2	10	250	2·50	3·00	0·069	0·750	0·691	22·50	
T_3	25	600	2·00	2·20	0·106	0·372	2·640	17·90	
T_4	50	600	2·00	2·20	0·114	0·464	5·680	45·95	Solder melted on overload, wire not fused; holder burnt in halves.
T_5	25	600	2·40	2·80	0·124	0·554	3·110	33·46	
T_6	50	600	2·00	2·40	0·141	0·775	7·030	75·40	
T_7	50	600	2·00	2·20	0·119	0·463	5·950	45·80	
V_1	5	500	1·00	1·40	0·647	0·647	2·590	2·59	
V_2	10	250	1·00	1·20	0·261	0·261	2·610	2·61	
V_3	25	250	1·00	1·12	0·545	0·545	13·630	13·63	
V_4	30	250	1·70	1·83	0·117	0·445	3·260	21·33	
V_5	50	250	1·40	1·56	0·220	0·367	11·000	22·04	
W_1	6	250	2·00	2·33	0·122	0·634	0·729	7·61	
W_2	6	250	2·33	2·67	0·119	0·737	0·714	10·33	
W_3	6	250	2·00	2·33	0·147	0·875	0·883	10·50	
W_4	30	250	1·43	1·60	0·323	1·048	9·040	45·00	
X	25	500	1·00	1·12	1·245	1·245	31·110	31·11	These fuses ran very hot owing to their excessive length & the small value of a.
X_2	50	500	1·00	1·20	0·948	0·948	47·380	47·38	

are typical sets of curves showing the voltage drop as a function of the current or percentage overload, while Figs. 4 and 5 show the watts losses corresponding to the voltage drops plotted in Figs. 2 and 3.

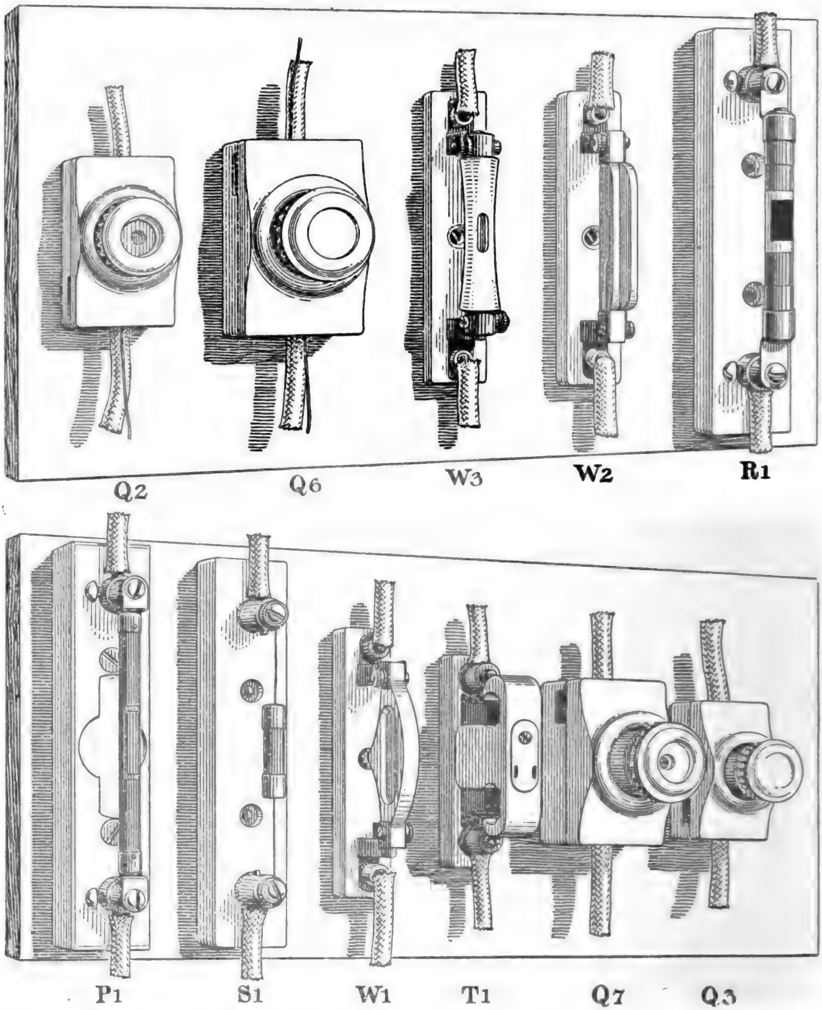

PLATE I.—Some Representative Types of the Fuses Tested.

Before proceeding to make any deductions from these results let us consider one or two points which may serve for general guidance. Taking first the case of a bare fuse wire stretched between two terminals, let us assume that a line of fuses, all of equal length, is to be

designed. It will be found that the voltage drop is proportional inversely to about the square root of the limiting current: thus, for example, fuses for 5 amperes and 50 amperes limiting current, which are to be rated at 50 per cent. or at 2·5 and 25 amperes respectively, will, if of tinned copper, have diameters:—

5 amperes limiting current	... ...	0·0145 cms.
50 amperes limiting current	... ...	0·079 „

At the same percentage of their limiting currents, corresponding in this example to the same percentage overload, the two fuses will have voltage drops proportional respectively to—

$$\frac{5}{(0{\cdot}0145)^2}, \text{ or } 23{,}800 \text{ for the } 2{\cdot}5\text{-ampere fuse,}$$

and—

$$\frac{50}{(0{\cdot}079)^2}, \text{ or } 8{,}010 \text{ for the } 25\text{-ampere fuse,}$$

so that the volts drop of the smaller fuse will be roughly three times that of the larger one. With a length of $3\frac{1}{2}$ in. the actual voltage drop when the fuses are run at 50 per cent. of the limiting current will be—

0·34 volt at $(5 \times 0{\cdot}5)$ amperes,

and—

0·11 volt at $(50 \times 0{\cdot}5)$ „

The corresponding figures for a current 90 per cent. of the limiting current are—

1·40 volt at $(5 \times 0{\cdot}90)$ amperes,

and—

0·47 volt at $(50 \times 0{\cdot}90)$ „

The drop of 1·40 volts is excessively high and would in most cases form a large proportion of the total fall of pressure in the circuit; the figure can be reduced either by decreasing the length of $3\frac{1}{2}$ in. between the terminals or by increasing the ratio of $\frac{\text{limiting current}}{\text{rated current}}$, *i.e.*, by using a larger wire and permitting a greater overload. Hence the same value of a is not advisable for large and small fuses; it may be desirable to increase the value of a as the normal working current diminishes.

In the case of fuses of the totally enclosed type, whilst the above remarks still apply, we have also to consider the effects of the increased cooling facilities and capacity for heat of the fuse enclosure. Owing to the large radiating surface, the size of wire for a given limiting current is reduced, and the drop of volts may therefore become large if the length of the fuse is not reduced or a metal adopted which has

a low melting-point. If the fuse is very short, on the other hand, conduction and dissipation of heat from the terminals will play an important part and exercise a similar influence in increasing the voltage drop and power loss. In order to reduce these two quantities to economical and safe limits, it becomes necessary to rate the smaller fuses at a lower percentage of the limiting current. Since well-

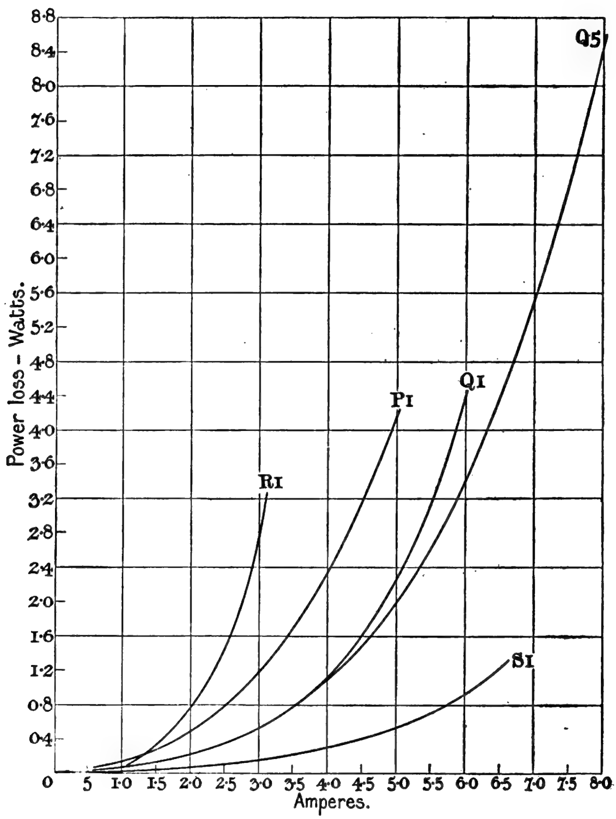

FIG. 4.—Power Lost in Fuses Rated at 4 Amperes.

designed fuses of the enclosed type may be made very much shorter than a corresponding open-type fuse for the same voltage, advantage should be taken of this possibility in order still further to reduce the losses; the alternative course of using a low melting-point metal is far inferior, and the larger volume of metal required may prove a source of danger. It may be noticed that it is open to the designer to rate the higher capacity fuses at the same low percentage of the

limiting current as the smaller sizes, but this again involves the use of an unnecessarily large volume of metal, a proceeding to be avoided as much as possible, particularly for fuses carrying heavy currents and liable to severe short circuits.

From a purely utilitarian standpoint it is probably correct that small fuses should carry higher overloads than fuses of large capacity, and all that might be said from this point of view may be best summed up by considering a 5-ampere fuse capable of carrying 10 amperes, and a 100-ampere fuse permitting a continuous load of 200 amperes.

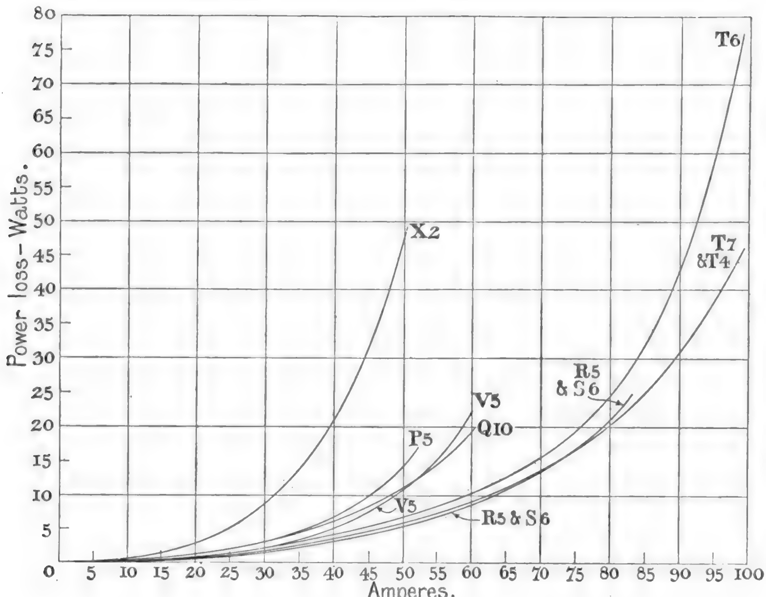

FIG. 5.—Power Lost in Fuses Rated at 50 Amperes.

The most important factor in determining a standard value or values for the ratio $a = \frac{\text{limiting current}}{\text{rated current}}$ is the maximum safe overload to which an electric circuit may, on the average, be subjected; the results arrived at from this consideration can, if necessary, be modified to meet the limitations of manufacture. The possibility of more economical utilisation of the apparatus protected is a natural consequence of adopting fuses which restrict within narrow limits the overload which may be imposed on a circuit. For fuses up to 50 amperes a maximum permissible continuous overload of 25 per cent.—as in the United States—is not wholly desirable, since most circuits and apparatus should be designed to withstand this amount

of overload without injury, and further, even the best system of non-interchangeability would fail and the circuits be overfused if users and wiremen found that they could not overload circuits to more than 25 per cent. even for short periods. Fuses run normally at only 20 per cent. under the limiting current must of necessity have fusible metal of low melting-point if the running temperature is not to be

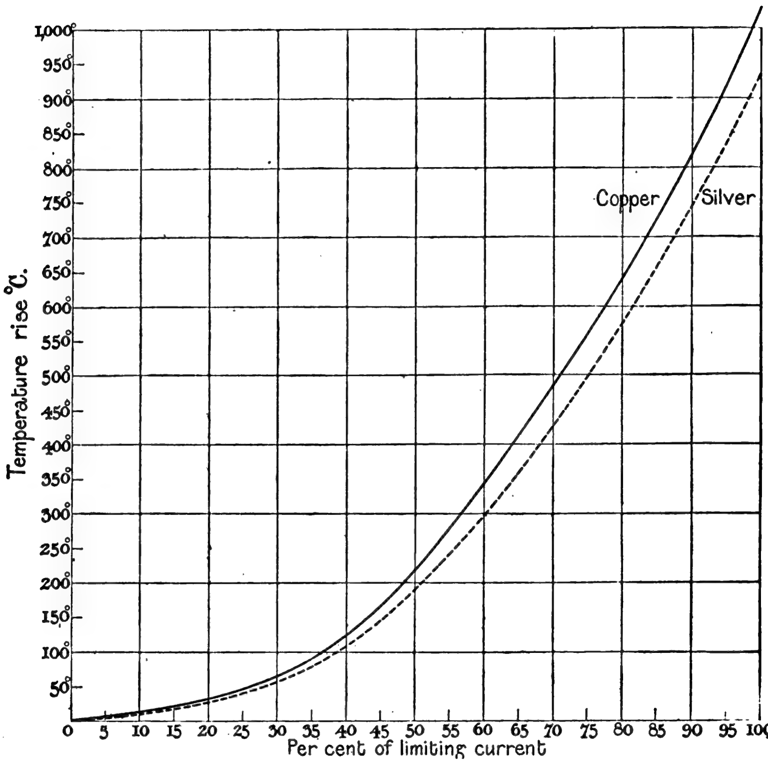

FIG. 6.—Approximate Temperature Rise of Copper and Silver Fuses in Relation to the Percentage of the Limiting Current.

unduly high; for reasons of equal importance the use of such metals is bad.

Nearly all the metals used for fuses suffer oxidation if run at temperatures much above that corresponding to 50 per cent. of their limiting current, although if silver be employed the rated current may certainly be as much as 65 to 70 per cent. of the limiting current without the occurrence of any deterioration. The permissible overloads corresponding to a rating 50 per cent. and 70 per cent. of the limiting current are 100 per cent. and 43 per cent. respectively, and

the large difference in these overload capacities is of interest as showing the superiority of a non-oxidising metal like silver if it is desired to reduce to a minimum the possible overload. Assuming, as will be afterwards shown, that copper and silver are the only metals suitable for standardised fuses, we can take as a rational basis—

Copper.—Minimum value of $\frac{\text{limiting current}}{\text{rated current}} = 2{\cdot}00$

Silver.—Minimum value of $\frac{\text{limiting current}}{\text{rated current}} = 1{\cdot}43.$

Returning for a few moments to the Table I., classes T, V, W, and X include fuses of tinned copper wire, and for all these the ratio *a* varies between about 1·12 and 3·0. The fuses whose symbol is X are rated at between 88 per cent. and 100 per cent. of the limiting current, and therefore the whole fuse-fitting became unbearably hot, with a current much below the rated value, whilst at the rated current of 25 amperes the fuse wire was red-hot and oxidising rapidly. On the other hand, the fuses T_5, which are rated at between 36 per cent. and 42 per cent. of their limiting current, contained about 2·9 times as much copper as the X_1 fuses, and are consequently far more dangerous on a high-voltage overload or severe short circuit.

Definite recommendations with regard to this part of the subject are reserved until other important questions have been discussed. Before passing on, however, attention may be drawn to Fig. 6, which shows the approximate variation of temperature of a bare copper fuse wire with increasing currents up to the melting-point and limiting current. The dotted curve is for silver fuse wire. The rapid rate at which the temperature rises after about 50 per cent. of the limiting current has been passed is noteworthy, and has an immediate bearing on the subject of rating.

(*b*) Standard Rated Current Values and Voltages.

For the limits of capacity now under consideration the standard voltages of 250 and 500 volts are certainly sufficient for all requirements at the present time. Whether two standard voltages are necessary is very doubtful, and the average performance of many types of fuse on 500 volts is such as to suggest that they might act better on a considerably lower voltage. An excellent plan seems to be the adoption of a standard voltage of 500 for all sizes, and the addition of a range of small capacity fuses for 250 volts for use on lighting circuits where small size and cheapness are important and very severe short-circuit conditions do not often occur.

In proposing a standard range of rated currents the important point is to reduce the number of sizes to a minimum while providing for all current values with a reasonable margin of overload capacity. It is necessary to take into account the values of the $\frac{\text{limiting current}}{\text{rated current}}$ ratio

discussed above, but provided the standard current values now commonly used are compatible with the adopted values of this ratio, there is little reason to do anything further than eliminate any redundant steps and put forward for general use the range settled upon. With bare wire, of course, any size will be used, finally the size which will not blow; but so far as the use of this type of fuse is allowed, any regulations or standards are useless.

A convenient subdivision is with steps differing by multiples of 5 amperes, giving, say, 5-, 10-, 15-, 20-, 30-, 40-, and 50-ampere sizes. At least one smaller capacity than 5 amperes is required, and since 4 and 6 amperes are standard values with a large number of manufacturers, a satisfactory completion of the range will be to adopt multiples of 2 amperes up to a value of 6 amperes, the complete standard line becoming:—

2, 4, 6, 10, 15, 20, 30, 40, 50 amperes.

(*c*) Definition of One or more Points on the "Time-current" Curve of each Fuse.

The main object in defining further points on the "time-current" curve of Fig. 1, in addition to the limiting current, is to ensure that the fuse will give adequate protection against very heavy overloads or short circuits, and to restrict within limits its sluggishness of action or "time element." From a practical point of view a regulation of this kind is useful because compliance with it can be readily checked, and it may be so framed as to eliminate the use of too large a mass of fusible metal and other faults of design. In order to be of real value such a regulation should require that a fuse shall melt within a fixed time—say 1 minute—when loaded with a certain multiple of its limiting current—say double that value. The actual time interval between the moment of switching on this overload and the blowing of the fuse would at the same time be taken as a practical measure of the "time element," although for this purpose a current less in excess of the limiting current would give a longer time interval capable of more exact observation. It will be convenient to return to this clause of our standard specification when finally deciding upon the question of rating.

(*d*) General Regulations for Construction and Operation.

While it is not desirable to specify too rigidly the constructional details to be embodied in standard fuses, yet it appears imperative that a few general principles should be laid down for the guidance of manufacturers, and one or two essential features should be demanded.

The extreme necessity of directing attention to some fundamental principles before fuse standardisation can be accomplished, is illustrated by two examples taken from samples tested by the author. A fuse (T_5 and T_6) made in several sizes for rated currents of over 20 amperes is of the protected or tubular type and of thoroughly substantial design,

Fig. A. Fuse class R4.

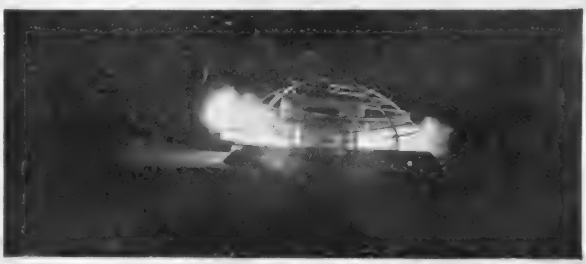

Fig. B. Fuse class T7.

PLATE II. (A and B).—Operation of Fuses on Short Circuit.

Fig. C. Fuse class S5.

Plate II. (C).—Operation of Fuses on Short Circuit.

the fuse wire, however, consisting of stranded tinned copper wire, is *soldered* at each end into a small terminal plate. The distribution of the masses of metal is such that all the fuses of this type which were tested opened the circuit by melting the soldered connection; had the full rated pressure of over 500 volts been maintained, the arc consequent on the separation of the wire from its terminal plate would have spread speedily and consumed the entire fuse fitting and terminals until the circuit was broken elsewhere. In a second line of fuses (R) of the totally enclosed or cartridge type, also rated for over 500 volts maximum pressure, a solid single link of soft fusible metal is used, containing a volume of metal nearly fifteen times as great as that contained in another make of cartridge fuse of the same rating. This protective device is completed as an explosive of a most dangerous kind by the provision of a number of vent holes in the metal cap at each end. Every principle of the design of enclosed fuses is ruthlessly violated, and, needless to say, the behaviour of these fuses on short circuit was of a violent description. A photograph of one of these fuses in operation on short circuit is included in Plate II.

If any efforts to increase the efficiency and serviceableness of fuses are to be successful it is inevitable that bare wire fuses should be abandoned, and the logical consequence of the standardisation of small capacity fuses is the introduction of a simple method by means of which the control of the fuse capacity on any circuit is placed in the hands of competent persons only. This requirement of non-interchangeability is far-reaching in its effect on fuse design since it involves the abolition of all fuse fittings having two exposed terminals, and in so doing leads half-way to the requirement dictated by safety, namely, that no terminals whatever should be exposed on fuse-fittings intended for use in private houses or public situations. Attention was drawn on page 622 to the fact that if an overload of 200 per cent. is permitted before the fuse comes into action, non-interchangeability becomes of the highest importance, since for small currents up to 10 amperes we may assume that fuse wire of "the next larger size" will increase the possible overload by some multiple of 200 per cent., rendering the circuit liable to overloads up to 400 per cent. or 600 per cent.

If the permissible overload is reduced to a much lower figure, for example, 50 per cent., less risk is indeed incurred by inserting the next size larger fuse, but if the circuit is faulty this process will be repeated several times until the size is arrived at which does not blow. An ideal system for safeguarding a circuit against overfusing should consist of some small separate part or adjustment which can be suitably set by an electrician either to restrict the capacity of the fitting to the present current or so as to allow a definite margin for increasing the size of fuse consistent with the dimensions of the wiring or apparatus. It is difficult to see how the requirement of non-interchangeability can be met to an adequate degree by any form of exposed wire fuse when we consider that enclosure of the terminals

must not prevent the non-technical user replacing a blown fuse by one of the correct size. Athough it is admitted that no non-interchangeable system will do away with the deliberate overfusing of the circuits, yet sufficient will have been attained if accidental overfusing is made impossible and an obstacle is placed in the way of using hairpins and similar well-known substitutes for the legitimate article. In their own interests, insurance companies should require the use of some system for preventing overfusing and should strictly forbid the use of any other conductor than the proper one intended for the fitting installed. A requirement of this kind would lead to the general use of the standard types which would become generally stocked and easily obtainable; the idea that the ubiquity of metal wire in some form or other justifies its indiscriminate use to nullify the purpose of a protective device would be gradually dispelled.

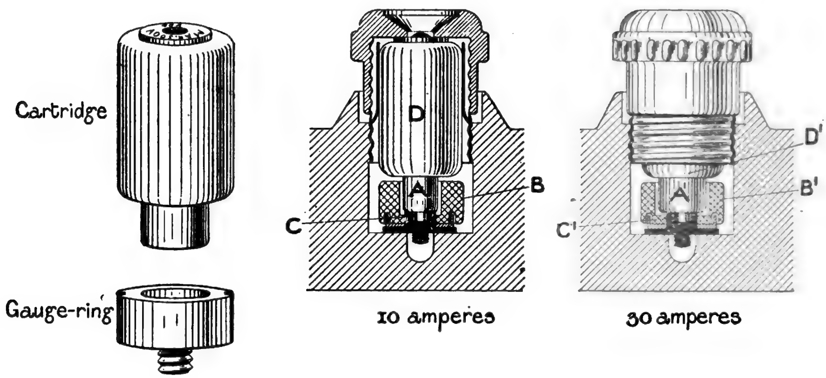

FIG. 7.—Example of Non-interchangeable Fuse System.

In order that the idea of non-interchangeability may be fully grasped, reference may be made in detail to what is, so far as the author knows, the only type of foolproof fuse on the market. Many varieties of non-interchangeable device have been employed in Edison plug fuses and allied types, but the design illustrated in Fig. 7 is a part of a fuse system which almost completely meets the requirements outlined in this paper. The loose pieces or "gauge-rings" B, B_1 consist of a steatite ring of constant external diameter, but having the diameter of the hole varying with the rated current. One of the terminals with which the cartridges D, D_1 make contact is situated at the bottom of the cylindrical hole in the steatite ring, and unless the stud A, A_1 is of equal diameter or smaller than this cylindrical hole, contact cannot be made. Thus B and D are gauge-ring and cartridge for 10 amperes, whilst B_1 and D_1 are the corresponding parts for 30 amperes rated current. The rings B for all capacities screw interchangeably into the same terminal block, but it is evident that a cartridge D_1 for

30 amperes will not make contact through its stud A_1 with the terminal C which lies at the bottom of a ring B for 10 amperes. It is, in fact, impossible to insert D_1 in a fuse fitting containing a gauge-ring B of smaller capacity. Needless to say, each rated current has its own special diameter of stud and gauge-ring orifice.

Bare wire fuses, or rather fuse fittings, in which a conductor can be easily inserted by the user, are incompatible with protection against overloading. Two other objections of equal weight against exposed fuse wire are :—

1. Their liability to scatter molten or hot metal.
2. The rapidity of corrosion unless certain non-active metals are used.

The first objection holds good of all metals, but more particularly of low melting-point metals, of which a larger volume is required than if copper or silver were employed. The second objection is especially applicable to copper, which in many other respects is an excellent fusible metal.

If, on the other hand, we examine the case for fuses of the totally enclosed type, we have the following outstanding advantages :—

1. The fuse wire is less liable to corrode or become injured, and therefore enclosed fuses lend themselves to exact calibration.
2. Tampering with the fuse wire is difficult, and a system of non-interchangeability is greatly facilitated.
3. If properly designed no molten or hot matter can be thrown about.
4. Perfect operation can be obtained on heavy overloads at full voltage.
5. Less metal is required, and the weight and size of the complete fuse fitting is reduced.

The principal objections raised against enclosed fuses are mainly questions of cost, the impossibility of inspecting the fuse wire, and the difficulty of ascertaining with certainty when the fuse has blown. The first-named objection appears to be almost wholly fictitious if account is taken of the frequency with which not only the fuse wire of an open fuse is melted, but the holder itself is either cracked or so fused as to be useless. Engineers do not seem fully to recognise how much more severe in many cases is the effect of fusion produced by a heavy gradual overload at full voltage as compared with the effect of a severe sudden short circuit. Fuses of the china holder type are often reduced to a useless condition by an overload, whereas they may withstand repeated short circuits of a severe character without great damage.

This is attributable partly to the fact that when fusion occurs on an overload the fuse wire melts at the centre and an arc is drawn out

and partly to the fact that the voltage is maintained on an overload, but a short circuit usually causes a main circuit breaker or another fuse to operate simultaneously, so that the circuit is broken in several places. The fact that a gradually increasing overload heats up the fuse fitting and diminishes its power of cooling the arc and vapours is also influential.

Plate III. shows a number of fuses which have been blown by gradually increasing overload on the normal rated voltage for which the respective fittings are sold. It will be observed that the majority of the damaged fittings illustrated are rated at 500 volts or over, and this

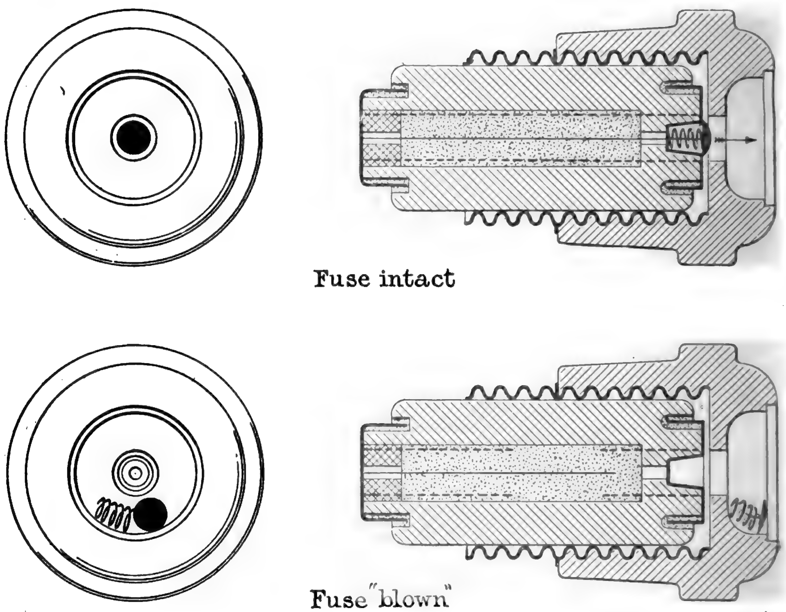

FIG. 8.—Example of Cartridge Fuse with "Self-testing" Indicator.

draws attention to the almost total absence of any type of open-wire fuse, which is reliable for use on high-voltage circuits. The asbestos protection now largely used, although fairly efficient when new, soon loses its efficacy after repeated blowing of the fuse, and is, moreover, frequently discarded altogether.

With regard to the deficiency of enclosed-type fuses in not permitting inspection of the fuse wire or giving reliable indication of fusion, the latter is a mechanical detail, which can be quite satisfactorily solved, as is shown by the arrangement adopted in a new type of enclosed fuse recently put on the market. Fig. 8 shows the design of indicator referred to. The diagrams are self-explanatory, and show that this device possesses the important advantage of being self-testing.

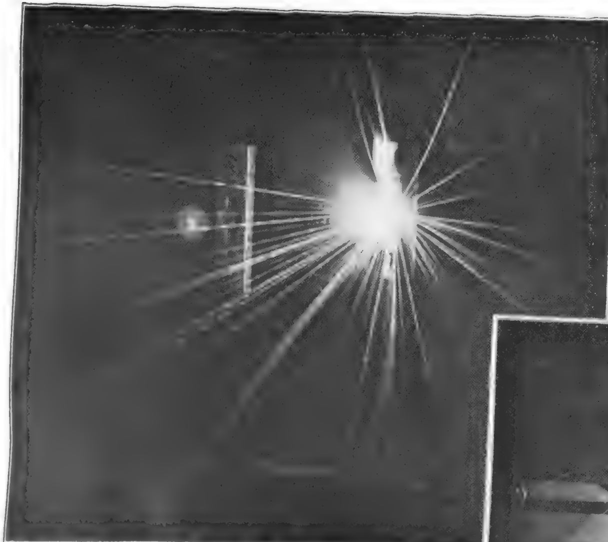

Fig. A. Fuse class R4.

Fig. B1

Fuse class T5.

Fig. B. Fuse class R3.

PLATE III. (A).—Operation of Fuses on Overload.

Fig. C. Fuse class V4.

Fig. D. Fuse class S5.

Fig. E. Fuse class X1.

Plate III. (B).—Operation of Fuses on Overload.

Fig. C. Fuse class V4.

Fig: D. Fuse class S5.

Fig. E. Fuse class X1.

PLATE III. (B).—Operation of Fuses on Overload.

Fig. F. Fuse class T4.

Fig. G. Fuse class S5.

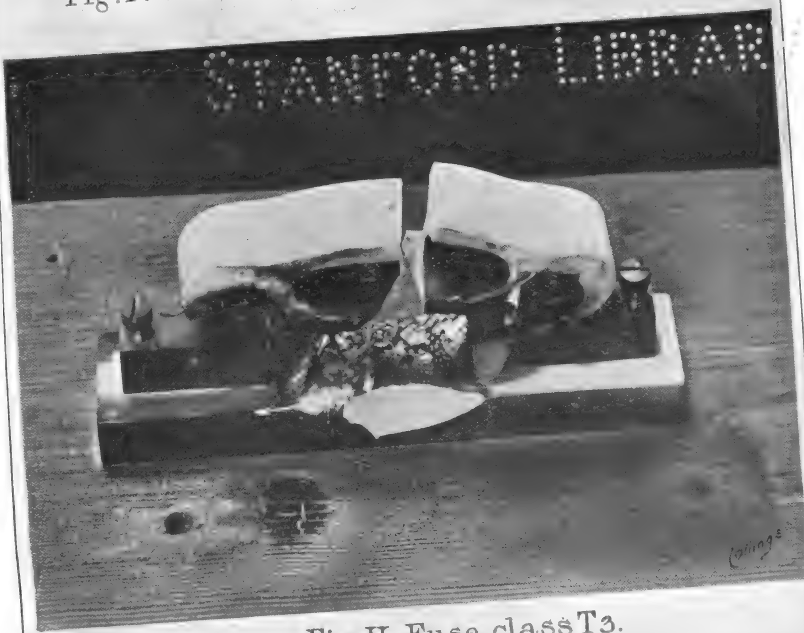

Fig. H. Fuse class T3.

Plate III. (C).—Operation of Fuses on Overload.

The demand for exposure of the fuse wire has arisen from the custom of inspecting a fuse, say of copper, either for the purpose of seeing what progress oxidation has made or to determine by its red glow or otherwise whether it was being unduly overloaded. The oxidation of a fuse is, as we have seen, harmful and unnecessary, and the rating and design of standard fuses should be directed towards minimising its occurrence; similarly a well-considered and consistent rating will in time enable the user to become familiar with the overload capabilities of a fuse of certain capacity.

For fuses of the capacity under discussion a completely enclosed design is the only one which enables any set of standards to be followed or enforced with reasonable success. In discussing the subject of the standardisation of fuses for the National Association of Underwriters, Lacount* states of a well-known type of enclosed cartridge fuse, which is widely used in the United States, that the "rarity of its misuse" is due to: (1) The Underwriters and Inspector's rules; (2) the readiness with which the cartridges can be secured in any location; (3) their reasonably low price; (4) the ease of replacement; (5) the difficulty in replacing the fusible wire.

Stress may be laid on four points essential to the satisfactory operation of any fuse whether of the open-wire, tubular, or totally enclosed type; these are :—

1. The volume of fusible metal should be reduced to the minimum compatible with correct rating and moderate temperature rise.
2. The fusible metal should be subdivided so that the ratio of exposed surface to cross-section does not fall below a figure depending on the design.
3. The provision of cooling arrangements adequate to extinguish the arc formed on overload.
4. In exposed wire fuses the provision of sufficiently free expansion space to prevent explosion when a short circuit occurs. In enclosed fuses the same end must be attained by precisely opposite means, and no opening or weakness of any kind is permissible in the enclosing case.

Fig. 9 shows four different makes of fuses, all for a rated current of 50 amperes, 500 volts, and all to the same scale. The black square at the side of each fuse represents by its area the volume of fusible metal in the respective casing.

While the fuse (No. 4) containing the least volume of metal operated perfectly under all overload and short-circuit conditions, and the fuse shown at the top (No. 1) which contains the next smallest volume of metal, and has a proportionately large casing also behaved satisfactorily, the two remaining samples consistently exploded or burnt often under the mildest circumstances. The great difference in the length of the

* *Transactions of the American Institute of Electrical Engineers*, vol. 24, p. 893, 1905.

four fuses is very marked, and the standard of excellence attained by each shows quite conclusively that attention to the four points enumerated above is necessary and sufficient for the production of a satisfactory article.

It is interesting to notice how the fulfilment of requirement (2) naturally leads to the cartridge design of fuse, since only in this design can the proper subdivision of the fuse wire be guaranteed. The effect of neglecting proper subdivision as well as the use of too much metal is shown in Plate IV., Figs. A. and B. It is unfortunate

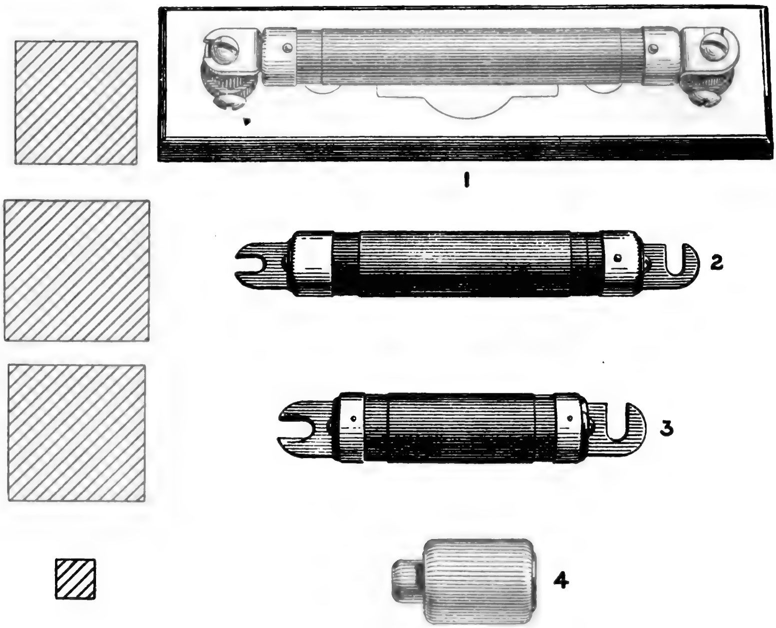

FIG. 9.—Comparison between Four Enclosed Fuses Rated at 50 Amperes, 500 Volts.

that instead of attacking the problem of an enclosed fuse in an appropriate manner, some designers have considered that the simple enclosure of an open-type fuse would produce the desired end. Provided that subdivision is properly carried out and efficient means of cooling the arc are employed, a fuse of the smallest size shown in Fig. 9 is far safer and more efficient than a much larger or longer fuse containing a considerable volume of metal, all of which may be vaporised on a short circuit. From this same point of view, the use of soft metals such as tin, lead, or zinc is to be deprecated, although with very careful design successful use may be made of the non-arcing property of the last-named metal.

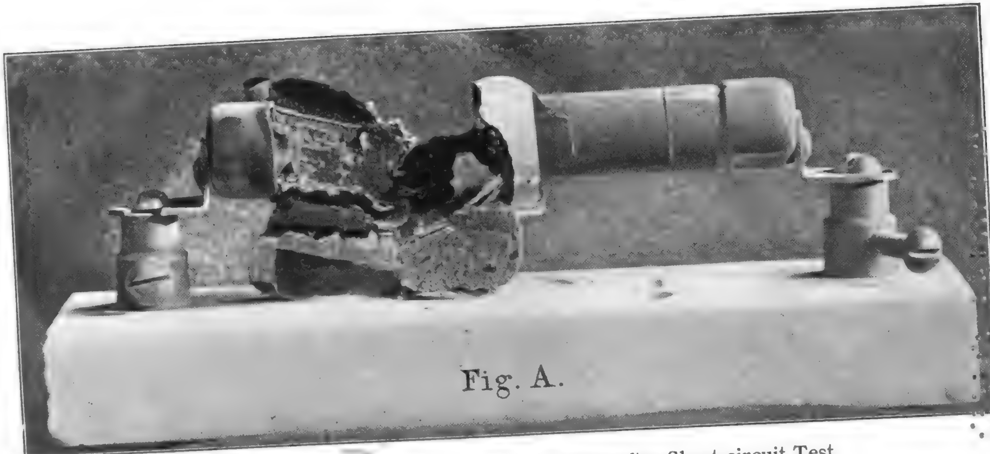

PLATE IV. (A).—View of Cartridge Fuse after Short-circuit Test.

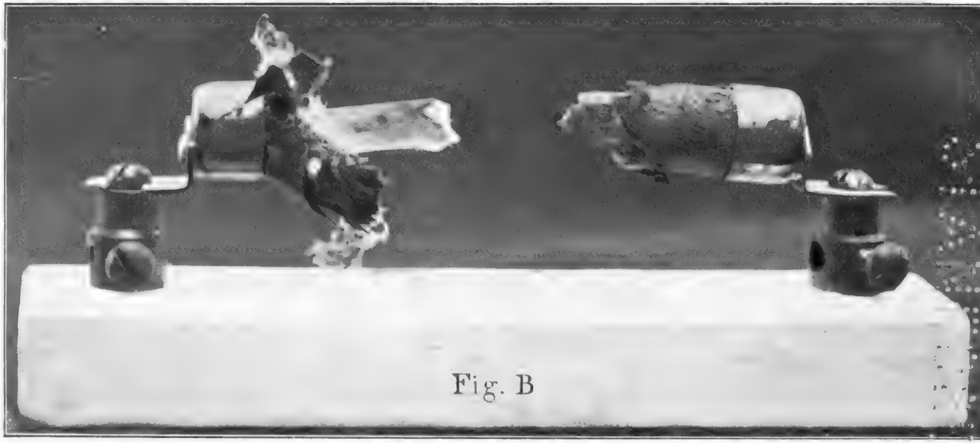

PLATE IV. (B).—View of Cartridge Fuse after Short-circuit Test, showing Effect of Excessive Volume of Metal.

The means at disposal for cooling an arc and condensing the vapours are three in number: by mechanical draught, by the surface condensation and cooling action of masses of porcelain, metal, or asbestos, and by the analogous use of an absorptive condenser in the form of filling powder. When the last method is adopted it is important that the fuse wire and filling should be free from any mutual chemical action even when subjected for a long time to alternate heating and cooling.

Fillings containing a capsule of liquid, or any hygroscopic or moist substance are bad in principle, and may be the cause of violent explosion or of chemical corrosion of the fuse wire. Tests carried out on a very large number of filling materials lead to the conclusion that the most suitable for use in enclosed fuses are thoroughly dry uniform powders of completely inert substance.

(*e*) Tests of Fuses.

The reliability and merits of a fuse are essentially matters to be submitted to the verdict of practical tests, which can be arranged to reproduce the exact conditions to be dealt with. The most important tests which a fuse must pass successfully in order to demonstrate its reliability are three in number :—

1. An insulation or pressure test (*a*) between all live metal parts and earthed metal parts, (*b*) between the two opposite poles of the fitting when no fuse is in place and when a blown fuse is inserted.
2. Tests for operation with gradually increasing current at normal voltage until fusion occurs.
3. Short-circuit tests at normal voltage.

In addition to the above tests measurements should be made of the temperature rise of accessible parts of the fitting and of the voltage drop. From the fire risk point of view the temperature rise of a fuse fitting should be taken as the maximum rise of temperature of any part of the fuse or fitting which is accessible when the fuse fitting is complete with its fittings and covers, etc., as in normal use.

Compliance with test 1 can be satisfactorily secured, and having been once demonstrated with a particular type or design, good insulation depends upon the maintenance of quality of the insulating materials and manufacture. A pressure test of at least 1,000 volts above the working pressure should be withstood without breakdown. Experience shows that under certain circumstances a risk of dangerous shock may be created by the use of hygroscopic materials like fibre, asbestos, or strawboard between the terminals ; leakage may occur sufficient to give a severe shock when it is thought that the operation of the fuse has rendered one terminal "dead."

Test 2 is of extreme value as an indication of the behaviour of the fuse under the conditions which in practice most frequently lead up to

fusion. The fuse under test should be connected in circuit with an adjustable resistance and a battery or generator giving the maximum normal voltage for which the fuse is designed. The current is increased gradually so that the fuse has time to attain approximately its steady temperature for each value of the current. This procedure is followed in three or four steps until the fuse blows. The circuit should not be opened by other means until all arcing or glowing has ceased. This test is a most useful one, and has great commercial importance since it represents the ordinary blowing of a fuse due to continued or slowly increasing overload. The whole of the fuse attains a high temperature favourable to the production and existence of metallic and other vapours, and the relative slowness with which the fuse wire heats, becomes molten, and is dispersed in vapour, is also, as compared with the rapid severance of the circuit produced by a sudden heavy overload, favourable to the continuance of an arc across the terminals. The formation of a continuous arc after fusion must be considered as a property even more dangerous than faulty performance under short-circuit conditions, the latter consisting generally of a violent explosion and scattering of the fuse fitting without necessarily giving rise to the great fire risk which always attends imperfect operation under gradually increasing overload. It is surprising how large a percentage of sample fuses utterly fail under this test.

The carrying out of the overload test calls for no special precautions; the voltage of the generator and the current should be observed throughout the test, and the current at which the fuse blows noted, as well as the duration of any arc which may occur, and the point at which it originates. For practical purposes this test furnishes a means of obtaining an approximate value of the limiting current.

Test 3. The value of a short-circuit test as a criterion of the goodness of a fuse depends to a large degree upon the manner in which the term "short circuit" is interpreted. The difference in the severity of the test is obvious, for example, between the case of a 10-ampere fuse short-circuited across a wall plug in a house installation and a fuse of the same size connected directly across the terminals of a 500-k.w. generator or battery. The latter test is very much more severe owing to the lower impedance of the circuit, which is responsible for a momentary short-circuit current of great magnitude, while the voltage across the fuse terminals is maintained at a high value.

A fuse of the smallest size may be inserted in an auxiliary circuit on the switchboard of a central station, in the closest proximity to the busbars transmitting thousands of kilowatts, and the safety of the whole plant may be imperilled by the failure of the fuse to sever a faulty circuit cleanly and promptly. Perfect operation on short circuit is a matter of careful design, and entails neither increased cost nor elaboration.

Since fuses of all capacities from the lowest to the highest are liable to be subjected to short-circuit conditions of the same severity, it is not advisable in specifying the method of carrying out short-

circuit tests to differentiate between fuses for various rated currents. Thus the "standard short-circuit" should not be defined as a maximum possible short-circuit current twenty or thirty times the rated current of the fuse under test, but all fuses for the same rated voltage should be tested in exactly the same circuit. An adequate but not too severe short-circuit test for fuses up to 50 amperes rating is provided by the following rules, which have been followed in all tests carried out by the author:—

1. The source of current should be a battery having an open-circuit potential difference 10 per cent. higher than the rated maximum voltage of the fuse under test, and capable of giving 500 amperes without the terminal voltage dropping by more than 5 per cent.
2. The total resistance of the test circuit including the fuse should be adjusted to correspond to a steady current of 1,500 amperes produced by an E.M.F. equal to the rated maximum voltage of the fuse.
3. On closing the main switch the fuse should blow without a continuous arc being formed or any explosive violence.

The following suggestions are put forward as a basis for the discussion of a specification for standard fuses:—

1. (*a*) *Material for Fuse Wire.*—The fuse wire must not corrode or permanently change its conductivity or physical structure.

(*b*) *Non-interchangeability.*—Fuses up to 50 amperes rated current should be provided with a simple arrangement by means of which the capacity of the fuse which can be inserted by a non-technical user is restricted within definite limits.

(*c*) *Type of Fuse Recommended.*—To facilitate compliance with (*a*) and (*b*) above and generally to render standardisation practicable and useful an enclosed cartridge type of fuse is recommended.

(*d*) *Indication of Fusion.*—All fuses must be provided with a simple means for detecting fusion simply by inspection of the fitting.

2. (*e*) *Rating.*—The rated current marked on the fuse shall bear a definite relation to the limiting current or least current which will produce fusion within 4 hours. The minimum value of the ratio $a = \frac{\text{limiting current}}{\text{rated current}}$ shall be 1·54 and the maximum value shall not be higher than 30 per cent. above the minimum. In a correctly proportioned line of fuses a should decrease from the maximum to the minimum values specified, as the size of the fuse increases from the lowest to the highest capacity. This regulation is based on the assumption that silver is the best metal for fusible links, taking into consideration its permanent character, the small volume required, and its "clean" action when breaking the circuit.

(*f*) *Sluggishness of Action and Time Element.*—Standard fuses shall be so rated and constructed that when loaded with 50 per cent. above the limiting current they will fuse within 1 minute. The actual time

required for fusion shall be taken as a measure of the "time element" of the fuse.

(*g*) *Standard Rated Currents and Voltages.*—Every fuse shall be clearly marked with its rated current and the maximum voltage for which it is suitable. The standard rated currents and voltage suggested are as follows:—

Maximum Voltage, 250.—2, 4, 6, and 10 amperes.
Maximum Voltage, 500.—2, 4, 6, 10, 15, 20, 30, 40, and 50 amperes.

3. (*h*) *Temperature Rise.*—When loaded continuously with 80 per cent. of the limiting current no exposed part of any fuse fitting shall attain a temperature exceeding 100° C. above that of the atmosphere.

(*k*) *Insulation.*—Fuse fittings shall be tested for insulation between terminals with the fusible portion removed and between the live parts and "earth" with the fusible portion in place.

(*l*) *Operation.*—Fuses shall be tested for satisfactory operation on overload and short circuit in accordance with the specified arrangements for carrying out such tests.

Discussion.

Mr. Crowley.

Mr. J. F. Crowley: I think it is desirable that fuses should be so standardised as to make it impossible for one of the wrong capacity to be put in circuit. I have known cases where fuses have been employed of a strength equal to that of the wiring. This is very dangerous, and gives a false sense of security to the station engineer or other person in charge. Mr. Kefford, in treating of the minimum limiting current of a fuse running on a current just sufficient to make it blow after a long interval, refers to four hours as a practical time to allow. I think that this should be increased to six hours or even more. I would also like a better definition of the "short-circuit test." The capacity and also the inductance of the circuit must be taken into account. Possibly one of the reasons for the somewhat chaotic state of the fuse question is that cut-outs are extensively used instead of fuses, but I am of opinion that for small currents fuses are the right thing.

Mr. Gott.

Mr. A. E. Gott: We have had several papers on fuses from time to time, but unfortunately they were of small practical value because the incalculable factors of all thermal devices, such as effect of external temperature and draught, cannot be neglected. The present paper on fuses is the most practical one we have had for some time. Whether it does or does not add much to the scientific side of fuse design, it certainly puts us on the right track for a solution of the question of what is a perfect fuse. I should like to take objection to the statement, at the bottom of page 620, that fuse selection is made on considerations of ornamentation. There are reasons for any and every variety of fuse design, though some of the reasons are sound and others are bad. Having searched twenty years' patent records of fuses, I

can distinctly trace the entire evolution of the fuse in these records; and although the various types of fuses now in use have evolved along different lines, there is no doubt we are getting nearer and nearer to the perfect fuse, and we have probably not reached finality yet. In fact, the time is not ripe for standardisation in such a manner as the author would wish. Generally speaking, I think he expects too much from fuses. At the top of page 623 the author refers to manufacturers working to a narrower limit. I am not quite sure what he means, but I take it he refers to working with greater accuracy and uniformity than we have hitherto seen. The real difficulty is that the small values of *a*, which he gives at the top of page 631, are altogether impracticable, and render electric supply internally unreliable. As an instance, I have vivid recollection of a brisk correspondence with a supply company some years ago over a motor installation. The 15-gauge fuse wire which the supply company insisted on for a certain motor was continually melting, to the annoyance of the consumer. Correspondence went on for a long time before a 14-gauge wire was substituted, and the trouble then disappeared. The real difficulty was that the supply company assumed the load diagram of the motor to be flat, but instead of being continuous it had peaks on it which melted the fuse, although the mean load did not overheat the motor in any way. In another case a supply company laid on power mains to a large newspaper office. The main fuse margin was totally inadequate, with the result that on the first occasion on which the proprietors printed the entire edition by electric power, the supply company's own man had to mop the fuses and terminals with waste and water for several hours till the edition could be run off. No fuse should be expected to save plant or lamps from overloads which, if continued, would injure them. The proper function of a fuse is to save plant, wiring, and appliances from destruction under very abnormal conditions, and if a fuse performs this, even at the cost of its own destruction, it has carried out its proper function. Where small values of *a* are required, the obvious method is to use a circuit breaker which can be set for any desired overload or time-limit, and has a constant rating. This is more reliable, and will dissipate about one-tenth of the power required by a fuse. Short fuses under certain conditions of induction fail to cut off the current, and many a switchboard panel has been ruined by their use. For this and other reasons supply authorities have insisted on definite lengths for certain currents and voltage, and the potential difference loss over such fuses is the price for real safety to the other apparatus. On page 627, by the author's own showing, the only way to reduce the voltage drop is either to reduce the gap—a thing which the supply authorities will generally not permit—or to increase the value of *a*, which is a contradiction to the object of the paper. The economical fuse of the future will probably be a fraction of an inch in length, but with mechanical means for increasing the gap at the moment of fusion. Several examples of this already exist, and though more expensive, they are cheaper than circuit breakers, which they replace

Mr. Gott.

Mr. Gott. to some extent by sacrificing the facility for rapid re-closing. Such a type can be so designed as to remove the objections made by many engineers to types in which the fusible material can only be replaced in a factory. Many engineers insist on fuses which can be quickly renewed from simple and easily procured material, and will not tolerate even soldered ends. Nothing has been said in the paper on the porcelain which forms the body of most fuses. As a general rule it is of very bad quality, and as there are numerous kinds for specific purposes, a careful selection would probably lead to less trouble than is usually experienced. Some qualities conduct heat more than others, and others again will withstand explosion better. Whether all the desired requirements can be combined in one quality or not is a matter for consultation with the pottery manufacturer. In reference to the author's opening remarks, I think the fuses should not always be blamed for the overloading of cables and wires. With large values of *a*, cables will be fully protected if they are of sections suitable for usual current densities. The author also stated that the limiting current is a perfectly definite quantity. I beg to disagree entirely with that, because the effects of draught have to be taken into account. With some types of fuses the opening of a door will alter both the limiting current and the conditions of the cut-out to a very great extent. On page 622 the author made some remarks in regard to the percentage of overload allowed by different authorities. My reasons for disagreeing with his proposals to reduce the overload percentages are sufficiently explained by my previous remarks.

Mr. Forster. Mr. A. L. FORSTER: I have found that the use of asbestos-covered wire for fuses reduces greatly the violence of the explosion when a fuse blows, and with such fuses I have not had any difficulty for some time. I think it would be of interest if Mr. Kefford would try this, and tell us of the effect. As to regulations for the interchangeability of fuses, we are all agreed that they would be of great value, but the day for them has not yet arrived.

Dr. Kloss. Dr. M. KLOSS: In reference to supply companies insisting on a definite minimum length between the poles of a fuse, this answers well with the old type of fuse which, when it blows, produces an arc, but it is not right that such restrictions should be made to apply to fuses in which no arc is produced. I would like to point out how important it is in drafting specifications not to stick to certain words which have been in use in past times, but always to specify what is required—the object and not the means. If the object only were specified the designer would be left freedom to develop new ideas. I maintain that restrictions as to length of fuses are not feasible, and are only likely to be detrimental.

Mr. Shaw. Mr. W. SHAW: I would like to know between what ranges the fuses are interchangeable and of such a type that they cannot be tampered with by an unskilled man. If the fuses are not interchangeable then trouble will be experienced in providing larger fuses, which might possibly be required through extensions. If, on the other hand, they

can be too readily changed, then the present-day trouble of inserting too large fuses would recur, as in dealing with larger currents for motors one generally meets with men of some experience who would very soon put up the gauge of the fuse. The idea of standardising fuses is very good, but it is absolutely essential that every possible condition be considered before standardisation can become a success. Mr. Shaw.

Mr. A. M. TAYLOR: The particular aspect of this question in which I am most interested is that of the fuses on a central station board. As far as possible, I think we rather avoid the use of fuses for the protection of anything but light circuits, and I looked through the author's paper in the hope of seeing some information that would bear upon this particular use of fuses, more especially as to the large rushes of current which may be expected through a fuse which is connected to a system of busbars behind which there is a large amount of power. I cannot help feeling that the rush of current on a short circuit is very considerably in excess of anything we anticipate. A short time ago Mr. Miles Walker * gave an oscillograph record of a short-circuit current from an 800-k.w. rotary converter, which showed that in $\frac{1}{1000}$ second the current rose to something like 14,000 amperes. That is a result obtained with only 800 k.w. connected to the busbars. With machines of greater power I suppose it would be at least in proportion and probably more than in proportion to the increase of power in the machine itself. In Mr. Walker's test the machine comprised the principal resistance in circuit. Let us consider for a moment what would happen from a purely theoretical point of view, taking the known data as to the amount of heat liberated in a conductor by a given current and the consequent rate of rise of temperature. First, let us consider a copper fuse exposed to the air, and let us assume that the normal temperature is 500° F., and that its melting-point is 2,000° F. (I have not the exact figures by me at the moment). Before therefore the fuse can melt it must be carried through 1,500° F. of temperature. Now, if we take the rate of generation of heat in a copper conductor due to a given current and neglect radiation and convection we shall certainly underestimate rather than overestimate the time which will elapse before the fuse melts. Take, now, the known data that a current density of 2,000 amperes per square inch gives a rate of increase of temperature of about 60° F. per minute, this will give us a rate of rise of temperature of 0·025° F. per second with a current density of 1,000 amperes per square inch. To fix ideas, consider a copper wire $\frac{1}{40}$ in. in diameter and 5 in. long, its cross-sectional area is roughly 0·0005 sq. in., and its resistance, cold, is roughly 0·007 ohm, we may tabulate results with such a wire as follows :— Mr. Taylor.

0·5 ampere = 1,000 amperes per square inch = 0·025° F. per second.
50 amperes = 100,000 amperes per square inch = 250° F. per second.
500 amperes = 1,000,000 amperes per square inch = 25,000° F. per sec.

Therefore, bearing in mind that the fuse has to rise through 1,500° F.

* *Journal of the Institution of Electrical Engineers*, vol. 45, p. 316, 1910.

Mr. Taylor.

of temperature, it would mean that the times taken would be theoretically as follows:—

$$0{\cdot}5 \text{ ampere} = 1{,}000 \text{ amps. per square inch} = \frac{1{,}500^\circ \text{ F.}}{0{\cdot}025^\circ \text{F.}} = 60{,}000 \text{ seconds.}$$

(*i.e.*, practically continuous rating).

$$50 \text{ amperes} = 100{,}000 \text{ amps. per square inch} = \frac{1{,}500^\circ \text{ F.}}{250^\circ \text{ F.}} = 6 \text{ seconds.}$$

$$500 \text{ amperes} = 1{,}000{,}000 \text{ amps. per square inch} = \frac{1{,}000^\circ \text{ F.}}{25{,}000^\circ \text{ F.}} = 0{\cdot}06 \text{ sec.}$$

So that at first sight from purely theoretical considerations it would seem possible to pass a current through such a wire corresponding to over 1,000,000 amperes per square inch, and yet not to generate sufficient heat to blow the fuse before the current had attained a value which, from Mr. Walker's test, might quite easily be attained in the $\frac{1}{1000}$th part of a second on a busbar system carrying only 800 k.w. of power behind it. I venture to think that not even the most credulous amongst us will believe that a copper wire of $\frac{1}{40}$ in. in diameter would carry 500 amperes for 0·06 second (or, say, 4,000 amperes for 0·001 second) before it fused, so that there would appear to be some factor overlooked in the argument, and I would be much interested to know if any of our fuse experts can throw any light on the question. At first sight it would appear to be due to an enormous rise in the internal resistance of the fuse itself, particularly near the melting-point; but this alone would hardly account for it, because according to some tables compiled by Clark and Sabine from tests made by Müller many years ago, it seems that the resistance of molten copper is only some eight times the resistance of cold copper, and there are no intermediate higher values before the melting-point is reached. This, therefore, would only reduce the above results ten times at the utmost, whereas one would expect that they would want reducing fifty to one hundred times. I raise the question in the hope that somebody will throw some light upon it, being confessedly unable to answer it myself. It may be remarked that if we neglect radiation the mere effect of my having taken a very small wire in no way vitiates the application of similar results to a wire or copper strip of much heavier dimensions. The same current densities should theoretically be reached. I should also add that if the current does attain anything like the values indicated, there must be set up tremendous effects of electromagnetic inertia across the fuse at the instant of breaking, and these would probably increase the ordinary disrupting effect on the fuse.

Mr. Morcom.

Mr. R. K. MORCOM: One thing that strikes me in regard to this question is that once things are standardised various authorities will be laying down limits, and my experience is that when authorities lay down limits they generally make them as inconvenient as possible. If this standardisation of fuses is carried through, and close limits are imposed, I am certain it will lead to even more tampering with fuse circuits than exists now. Safety devices are often a nuisance in prac-

tice, and are treated as such. I was in a tramway station in South Africa where they had a number of automatics, and every one was tied up. Again, on the Continent, I was in a hotel where the lights in the various guest rooms were continually going out because the fuses were so very close. All one had to do, however, was to take a two-franc piece and put it across the terminals, so preventing the inconvenience. Mr. Morcom.

Dr. D. K. MORRIS (*communicated*): The author gives at the end of his paper a suggested basis for a specification for standard fuses. As a device for opening a circuit on overload through the heating effect of such overloads, the fuse has until recently been the only apparatus available. It is interesting, however, to notice the remarkable way in which the thermally operated time element circuit breaker now meets the conditions of the author's specification. Taking the clauses in order, we note (1) that the thermal breaker, being operated at a low temperature rise, is quite permanent in its rating; in a breaker not fitted with adjustment the releasing current cannot be altered and the breaker can be clearly marked; the breaking of the circuit is obvious from the position of the arm; (2) the rated current can be as much as 80 per cent. of the limiting current (as compared with 50 per cent. for a good fuse; (3) the loss of watts in the thermal strips is approximately one-fifth that of a fuse, and the temperature rise is 50°, not 100° C. As a means for breaking a circuit the thermal breaker can be properly designed to meet severe conditions with carbon and auxiliary metal break or magnetic blow-out. In fact, it meets all the requirements laid down by the author's specification. In addition, the circuit is always ready for immediate closing without the delay that arises in replacing and re-wiring a fuse. In all cases, therefore, there would appear to be a great advantage in using thermal circuit breakers in place of fuses. Dr. Morris.

Mr. H. W. KEFFORD (*in reply*): I think that Mr. Taylor's remarkable conclusions are partly due to his having neglected to take into account the rise in resistance of the copper or other fuse metal with its temperature, which would greatly decrease the time taken to blow the fuse, and would help to bring the results of calculation and observation into line. At the same time, it is perfectly true that the momentary current rush on short circuit might approach very closely to the maximum value, corresponding to the impressed voltage and the impedance of the circuit. I would ask those speakers who hold the opinion that the time is not yet ripe for standardisation whether a more favourable time is ever likely to arrive. We now have at our disposal the experience and results of the fuse standardisation adopted by other nations, and no further time should be lost in attacking a problem which is rendered more and more difficult and complex the longer action is deferred. There is, of course, an innate conservatism in this country which adversely affects any movement of this kind, but I believe that just as standards have proved highly beneficial in the realm of mechanical engineering, so would the standardisation of fuses and Mr. Kefford.

Mr. Kefford.

similar electrical apparatus be regarded as a necessary and profitable step by those who have had a large experience in using or designing fuses, or who are interested in adding to the safety and convenience of electrical installation of all kinds. Although it may be difficult to observe accurately the limiting current of a fuse, this quantity is just as definite as the specific heat or electrical resistance. If an accurate determination is to be made all disturbing factors must be eliminated. For all practical purposes the limiting current can be obtained with sufficient accuracy on the basis of a 4 hours' run. Tests have shown that the difference in the currents required to effect fusion in 4 hours, and 6 or even 10 hours, is so small as to be negligible for all ordinary purposes. Short-circuit tests should certainly be carried out under well-defined conditions if the results are to be comparable with one another, and the most practicable arrangement appears to be the use of one or two specified central station batteries throughout the country for the purpose of standard short-circuit tests. The wide variations liable to occur in the self-inductive end capacity properties of different sources of current would be eliminated, and the details of the remainder of the circuit as regards these properties could then be laid down with exactitude. I do not agree with Mr. Gott that a fuse should not be expected to save plants from overloads, since this is a function for which properly designed fuses are in many cases more suitable than circuit breakers. It is as important to protect circuits from prolonged overload as from sudden short circuit. As pointed out by Dr. Kloss, there is no occasion whatever for supply authorities to specify the minimum length of fuse; the object in view is the safe and rapid extinction of the arc, and this could be ensured with far greater certainty in a properly designed enclosed fuse having a 1½ in. break than in an open-wire fuse of three times this length. I am very glad, in one sense, to hear that Mr. Shaw has had trouble on one occasion owing to the non-interchangeability of a fuse, since the effectiveness of the device is thus demonstrated. The particular Siemens non-interchangeability system described in the paper is at present used for normal carrying capacities up to 60 amperes at 500 volts, but will be extended eventually to much larger sizes. It should be borne in mind that the non-interchangeability device could be dispensed with at the discretion of the supervising engineer, since it is the maximum current which the gauge-piece determines, and by using the largest possible gauge-piece any fuse cartridge can be inserted at will.

ISOLATED ELECTRICAL PLANTS.

By R. C. PLOWMAN, Student.

(Abstract of Paper read before the Students' Section in London, March 16, 1910).

Competition with Imported Supply of Current.—Very early in the consideration of the subject of isolated, or private, electrical generating plants comes the question of the economy or otherwise of such plants over a possibly available supply of current from without. Many supply authorities in England, supplying or seeking to supply energy at rates competitive with the total cost (including both capital and running expense) of privately generated current, do so at prices which it would seem cannot possibly be remunerative to an undertaking with a predominating power load and a large capital expenditure per kilowatt of plant installed. This matter was thoroughly thrashed out by Mr. J. F. C. Snell in his paper, "Cost of Power for Industrial Purposes," * read before this Institution in 1908. Mr. Snell's conclusions were in the main strongly supported by his audiences, and the figures which he set forth are therefore taken by the author as the lowest remunerative rates at which current can be supplied by the authorities mentioned in his tables. From a comparison of Table VII. in Mr. Snell's paper and Table I. (page 650) two important conclusions may be drawn:—

1. That there is no central station in London (with the exceptions, perhaps, of Hammersmith and East Ham) which is supplying current at competitive rates for power purposes, which is also making a sufficiently large charge to cover the total cost of production, and, further, to make a profit.
2. That those stations supplying at or above the correct rates are doing so at rates which authenticated figures show are not competitive with the cost at which current can be supplied by a well-designed private plant of a fair size.

Cost of Power from Private Plants.—The latter conclusion should be evident from a scrutiny of the figures comprised in Table I.

To effect a saving over the local plant, the advantage of cheaper generation possessed by the larger station must be sufficient, after allowance has been made for a reasonable profit on the undertaking, to wipe out the heavy capital charges incurred on the transmission feeders and

* *Journal of the Institution of Electrical Engineers*, vol. 40, p. 288 *et seq.*

TABLE I

Cost of Current generated by Various small Stations.

Motive Power.	Capacity of Plant.	Nature of Load.	Annual Load Factor = Units / 8,760 × k.w. installed	Approximate Total Running Hours per Annum.	Fuel Cost per Ton. s. d.	Annual Costs per Unit.	Remarks.
Steam.	336 k.w.	Shipyard and engine-works	0·41	7,500	11 6	0·935	Total costs.
	640 "	Steelworks and engine-works	0·38	7,500	9 8	0·675	"
	250 "	Small colliery ...	0·22	8,000	1 6	0·725	"
	672 "	Engine works ...	0·22	2,700	—	0·710	"
	500 "	Paper-mill	0·75	7,000	—	0·337	"
Suction Gas.	150 "	Small central station...	Probably about 0·12	8,760	36 8	0·749	Works cost only.
	450 "	Storage battery, works and factory	0·55	7,000	—	0·400	Total costs.
	450 H.P.	Cement works ...	0·70	7,000	20 0	0·324	"
	300 "	Weaving shed ...	0·25	2,700	20 0	0·365	"
	20 "	Small factory	0·13	2,700	20 0	1·175	"
Diesel.	200 k.w.	Small lighting station	0·16	8,760	53 11	0·395	Works cost only.
	160 "	Industrial	0·45	3,750	Probably about 55s.	0·725	"
	400 "	Motor-car works ...	0·25	2,700	Probably about 55s.	0·355	"

distributing networks, and under many conditions which are quite ordinary in the present-day extended use of electric power, an advantage of this magnitude is unattainable, and there remains in consequence, at any rate on the score of economy, a wide field for the private plant for factory operation and similar heavy duties.

Merits of Outside Supply.—The other factor in the situation is that of convenience to the consumer. Central station power promises continuity of supply without responsibility to the owner, ensures his independence of strikes in other trades producing the materials for generation, leaves him free to contemplate extensions without regard to the provision of additional power plant, and is supposed to set free his capital for investment in further productive machinery.

Other General Considerations.—In small works up to, say, 100 H.P., a straight fight between the external and internal plant would, and ought, nearly always to result in favour of the central station; but in many large works the issue is complicated by certain other considerations. There are many works, for instance, which must of necessity make use of a large supply of steam in other places than in steam engines. Thus less than half the steam used in a paper-mill is consumed by the engines, the rest being required for various heating and drying requirements in the manufacture of paper. There are many similar works where steam has to be raised in any case, and where the taking of an outside supply in no way secures the entire scrapping of boilers and abolition of stokers' wages.

Again, many operations such as flour milling, cement crushing, paper pulp beating, etc., require a large amount of power, some hundreds of horse-power it may be, on a single machine. In a case like this there is rarely any need for electrical transmission at all, as it must always be remembered that one cannot claim more than 90 per cent. efficiency for electrical transmission, and this value is almost within the range of compact mechanical transmission by a short, stiff, line-shaft, or even of the direct carriage of steam in properly lagged and short steam pipes. Therefore it is generally possible, and most economical, to drive the heaviest machines through a compact mechanical transmission, or in some cases the driving engine is actually incorporated with the machine which forms its load. But in works of this description there will generally be a number of scattered auxiliary machines which present an admirable case for electric driving, and it will be shown how in the case of a paper-mill typical of works of this class it would obviously be better to obtain these electrical units from the works' own boiler plant rather than from the boilers of a central station at a considerable distance away.

The Power Problem in Particular Works: I. *Textile Mills.*—The cotton-mill provides one with a good instance of power having been generated on the premises without hitch or trouble for years on end, and where the mill-owner cannot see any reason why he should wish to import current because he intends to change the method of trans mission of power between engine and machinery; that is to say

providing he cannot import current more cheaply than he can generate it.

Cotton-mills usually owe their geographical situation to the fact that coal is present in abundance close at hand, and therefore it follows that coal is a comparatively cheap commodity to the mill-owner. He can, in fact, purchase coal almost, if not quite, as cheaply as can the power station in the same district, and the mill set is usually sufficiently large to ensure economical consumption of steam. Moreover the neighbouring power station with a mixed load, most of it possessed of a bad load factor, will certainly not have as good a load factor as the cotton-mill. Rarely, indeed, will it have one which is one-half as good. Hence the larger station does not appear to have much advantage in generation, and what there is will probably be wiped out by the heavy cost of transmission, which must be borne by some one, before the mill is finally reached.

The conditions in the mill make a further demand which is in favour of the isolated plant, in that a large quantity of steam is required annually to keep the atmosphere humid in the mule-sheds, and to ensure a warm atmosphere throughout the mill in winter, a point to which textile manufacturers pay much attention.

How all these considerations appear in figures is shown by Table II., which gives a digest of Mr. W. H. Booth's estimate of the capital and running costs in a textile factory, both when current is purchased from an external source and when it is independently generated.

It will be seen that on account of the high average load in the mill, 900 k.w. on a 1,000-k.w. engine, the cost of current is enormous, in spite of the fact that the estimated charge for current is very low, viz., 0·5625d. per unit. Now, assuming for the sake of argument that the mill is in the area of supply of the Manchester Corporation, it is seen by reference to his paper,* that the price which Mr. Snell estimates should properly be charged by this authority, when the annual load factor is 30 per cent., is 0·86d.; so that the price which is taken by Mr. Booth must be regarded as a very moderate one. Yet in spite of this price the cost of power in the mill when current is derived from without is 0·657d. per unit against a cost of 0·541d. per unit from the works' own plant.

Granted that the mill can generate current more cheaply than it can buy it, we have not yet quite fully appreciated the mill-owner's point of view. Electrical transmission is at the bottom of the benefits which electricity has to offer in the textile mill. It has been proved that electrical transmission in the room of mechanical transmission increases the output of the mill some 5 per cent., because it renders safe an increase in the speed of the spinning frames. With mechanical transmission one cannot run at the highest frame-speed actually possible, because if one did there would come a time when, with an irregularity in speed of shafting due to fluctuating local load, the speed would be

* "Cost of Power for Industrial Purposes," *Journal of the Institution of Electrical Engineers*, vol. 40, p. 311, Table IX., 1907.

TABLE II.*

Comparison between Total Capital Cost and Annual Running Costs in a Textile Mill driven (a) *by Independent Plant, and* (b) *with Purchased Power.*

With Independent Plant.				With Purchased Power.			
Total Capital Cost.		Annual Running Cost.		Total Capital Cost.		Annual Running Cost.	
Expenditure on	Amount.	Item of Cost.	Amount.	Expenditure on	Amount.	Item of Cost.	Amount.
	£		£		£		£
1,000-k.w. Turbo-generator, condensing plant, engine house, and foundations	7,300	Coal, 4,300 tons at 12s. 6d. per ton	2,690	Boiler, piping, pump, etc., for heating, boiler-seating, and chimney	850	Coal for heating, 300 tons at 12s. 6d.	188
Four 30 ft. × 8 ft. Lancashire boilers, superheaters, boiler-house, seating, chimney, and economisers	5,300	Wages	325	Transformer house	300	Wages	138
Reservoir (if necessary) ...	1,500	Oil and stores	75	Transformers, including spare set	1,000	Oil and Stores	50
Switchboard, cables, and motors	4,000	Insurance	258	Motors, cables, and switch-board	4,000	Insurance	125
Mill-gearing	2,080	Rates, 7s. on 5 per cent. of capital outlay	373	Boiler house	150	Rates, 7s. on 5 per cent. of outlay	162
75-k.w. lighting generator, switchboard, and wiring for 1,200 lights	1,710	Interest and depreciation	2,644	Switchboard and wiring for 1,200 lights	900	Interest and depreciation	1,112
						Current on average load of 900 k.w. at uniform charge of 0·5625d. per unit	5,906
Total	21,890	Total	6,365	Total	9,280	Total	7,681
Total cost per unit on assumed running load factor of 90 per cent., 0·541d.				Total cost per unit on assumed average load of 900 k.w., 0·657d.			

* From figures given by W. H. Booth, *Electrical Review*, vol. 63, p. 903.

increased beyond the allowable maximum, and broken threads would result. But with 3-phase motors, local fluctuating loads will not affect the driving speed at all, as such speed will be governed by the frequency of supply; hence the maximum possible speed may be adopted right away as the average running speed. This increases the output of the frames very considerably, and is a point of immense importance. The mill-owner therefore wants electrical transmission rather than electric power, if one can draw such a distinction, while maintaining absolute reliability in the source of power. Both these he can do by tacking on electrical transmission to his own engine, where this is one of the highly perfected and economical engines such as are customary in mills of the kind under consideration. Such an engine has probably never failed him, and his very strong faith in it is fully warranted by experience. Consequently the author considers that the most satisfactory conversion to electric driving in these cases is by means of power generated by a 3-phase alternator direct-coupled to the mill's existing engine—usually of the cross-compound slow-speed reciprocating type. Engines of this type usually have a cyclic irregularity as low as one-half of 1 per cent., and this gives almost as near an approach to absolute constancy in speed as does the turbine, generally recommended for textile work.

II. *Paper-mills.*—Paper-mills again present a problem of motive power supply which is not solved merely by a competition for cheap generation between the central station and the isolated plant. As previously mentioned, it is not uncommon for as much as 60 per cent. of the steam used in a paper-mill to be required for manufacturing purposes, even when the fullest possible use is made of exhaust steam in the paper machines, calenders, etc.

The first requirement of a paper-mill is for heat rather than for power; hence the power, though demanded in large amount in a mill of any size, is not the most important consideration in the lay-out of a paper works. Consequently there are very few instances of works of this kind being driven electrically, with a separate system of live steam supply to those machines requiring heat. We have therefore a large boiler plant not only for power, but also for drying, boiling, warming, glazing, and other operations, and imported electrical power offers a comparatively unimportant prospect of shutting-down boilers.

This will be more plainly seen from Table III., which is an analysis of figures given by Mr. T. Y. Nuttall* in 1906 before the Paper Makers' Association of Great Britain and Ireland, which show the disposal of heat and power in a paper-mill laid out on up-to-date lines, and in which electric power is used to drive the auxiliaries only. From this table it will be seen that the biggest items in the energy bill, either for power or for heat, are:—

1. Power required to drive the heavy machinery dealing with the raw material in its early stages (item 1).
2. Heat required to dry the paper (item 4).

* "Comparative Cost of Steam and Water Power for driving Paper Mills," by T. Y. Nuttall, *Paper Makers' Circular*, December, 1906.

TABLE III.*

Showing Consumption of Energy required to Produce 1 Ton of Paper per Hour, and the Portion of Load to be borne by Works' own Electrical Plant.

Section of Plant.	Work Done.	Consumption of Coal.	Average Load in Horse-power.	Cost per Hour. Coal.	Cost per Hour. Working Expenses.	Cost per Hour. Interest and Depreciation.	Cost per Hour. Total.	Per Cent. of Total Cost of Production of 1 Ton of Paper.
				s. d.	s. d.	s. d.	s. d.	Per Cent.
Main engine: compound, condensing	Driving breaking, bleaching, and beating plant	1·75 lbs. of coal per I.H.P.-hr.	450	2 9½	1 4½	1 4	5 6	41·2
Steam-driven electrical plant	Driving pumps, hoists, cutting and reeling machines, super-calender, repair shop, etc.	2·25 lbs. of coal per I.H.P.-hr.	100	0 9½	0 3½	0 5	1 5½	10·9
Paper-making machines; steam engines incorporate with machines, and exhausting into rolls to keep them hot	Paper-making proper	0·4 lb.† of coal per I.H.P.-hr.	180	0 3	0 7	0 4	1 2	8·7
Boiler plant	Drying paper ...	0·5 lb. of coal per 1 lb. of paper	—	4 0	—	—	4 0	30·0
Boiler plant	Requirements of steam for miscellaneous purposes, such as heating calenders, "stuff," warming works, etc.	Assessed after experiment at 3 cwt. of coal per hour	—	1 2½	—	—	1 2½	9·1

* Compiled from T. Y. Nuttall's figures. Paper Makers' Association, December, 1906.
† Equivalent consumption, as, during exhaust, the same steam does useful work warming rolls.

The first requirement can be efficiently met with simple mechanical transmission, as these machines are always arranged compactly with respect to the main drive, and there is nothing to be gained by a double conversion of energy through dynamos and motors. The second requirement (item 4), as also item 5, obviously cannot be met electrically.

Then with regard to item 3 in the table, it must be borne in mind that the figure of 0·4 lb. of coal per I.H.P. is an inferential one, which can only be included when the exhaust steam from these engines does useful work in drying the paper on the machines incorporate with the engines, thus reducing item 4 for paper drying in the heat sum of the whole mill.

Consequently, if we took out the steam drive of the paper-making machines, and substituted electricity, we should have to charge more nearly 2 lbs. of coal per I.H.P.-hour to item 3, thereby increasing it some five times, and the boilers would still have to supply the heat necessary to dry the paper. So that from this standpoint electricity would mean a higher cost of production of the paper.

We therefore conclude that only about 11 per cent. (item 2 in the table) of the total energy required in the mill can be economically met electrically, and we now have to decide whether this power can best be supplied from outside or from the works' own plant. Now all the power necessary to drive these scattered auxiliaries is latent in the exhaust steam from the main engine driving the beating machines (item 1, Table III.) by line-shaft, or in that of the several beating engines if these machines are individually steam-driven. In any case an exhaust steam turbine can be coupled up either to the one engine, or to a number of the individual engines through a common receiver. This turbine will supply all the power necessary for the auxiliaries and for lighting the works, without any material increase of coal consumption under the main boilers. The annual cost of power, therefore, will be simply capital charges plus running charges on the turbine plant, and the latter will amount to nothing more than the cost of oil, waste, and stores, as wages, like coal, will not be increased. Assuming, for example, a load of 250 k.w., the first cost of the turbine plant will be, say, £4,000. Then total annual cost of power incidental to private plant will be—

	£	s.	d.
Capital costs, 15 per cent. on £4,000 ...	600	0	0
Running costs, 1,500,000* units at 0·075d. per unit	468	13	0
	1,068	13	0

Now total annual cost incidental to supply from outside will be, at a purchase price of, say, 0·075d.—

1,500,000 units at 0·75d. = £4,687.

* Assuming annual load factor of 75 per cent.

Showing a saving by adopting the independent exhaust steam plant of about £3,620 per annum, a very considerable sum.

The above facts make out an obvious case, in the author's opinion, for localised electrical generation for the purpose of driving the auxiliaries in a paper-mill, and the prime mover should certainly be an exhaust-steam turbine supplied with steam from the beater engine.

TABLE IV.

Description of Working of a Small Colliery Plant, running non-condensing and burning "washings."

Description of Plant.

Engine: 365-H.P., 2-crank, compound, non-condensing, 125 lbs. per square inch pressure, 375 revs. per minute.
Boilers: Two Lancashire boilers, 150 lbs.
Dynamo: 3-phase, 250 k.w., 500 volts, 50 cycles.

Capital Outlay.	£	s.	d.
Engine, generator, switchboard, etc.	1,400	0	0
Boilers	873	0	0
Buildings, foundations, piping, etc.	516	0	0
Total	2,789	0	0

Annual Running Costs.	£	s.	d.
Wages of two enginemen	194	13	4
Wages of one fireman	82	3	6
Coal, 3,600 tons at 1s. 6d. per ton	270	0	0
Oil, waste, and stores	10	0	0
Total	556	16	10

Annual Capital Charges.	£	s.	d.
Depreciation and upkeep of engine, generator, switchboard, etc.	110	0	0
Depreciation of boilers	58	4	0
Depreciation of buildings	20	13	0
Upkeep of buildings	10	6	0
Interest at 6 per cent. on capital outlay	167	8	0
Total	366	11	0

Output for November, 1909	25,429 units
Running cost per unit	0·438d.
Capital cost per unit	0·287d.
Total cost per unit	0·725d.

III. *Collieries.*—Collieries again present a case where, viewing the matter on logical and impartial grounds, one is led to the conclusion that there is a wide field for the isolated plant in the industry concerned.

At the very start, coal is cheaper at a colliery than anywhere else, for it is present in abundance at a market value which is sometimes nothing, and sometimes any price up to, say, 1s. 6d. per ton. Such coal is variously known as "smudge" or "washings," and every colliery has more of it than it knows what to do with. Granted that the local plant must burn far more of such fuel per unit than a central station burning decent coal, such a plant can still generate much the more cheaply of the two. Yet a great deal will depend upon the kind of load on which the power generated is to be used. If it be on haulage only, with a load factor very often of about 5 per cent., the capital charges will be disproportionate, and the outside supply will be able to compete successfully. But given an average load with a fair amount of pumping and ventilating included, the inside plant will be a long way cheaper than the outside. Table IV. gives particulars of the running of a small colliery plant of 250 k.w. The plant runs on an average load factor of about 20 to 25 per cent., using coal worth about 1s. 6d. per ton at the most. The engine runs non-condensing, with hand-fired Lancashire boilers, and the consumption of coal is at least 20 lbs. per unit, against a probable figure of, say, 4 lbs. in the central station. In spite of this the cost per unit in the month of November last, when the test was taken, was only 0·727d. per unit, and since then the cost has been coming steadily down as the load on the set is increasing. The load consists of hauling, pumping, coal-cutting, and rock-drilling, and the running hours are 168 per week.

Even under the above ordinary conditions, therefore, the localised plant comes out considerably cheaper; but under conditions which are not more special in a large colliery, viz., where an exhaust-steam turbine may be coupled up to a powerful winding engine, we have a similar state of affairs to that described for the paper-mill, and there is again no comparison between the internal and external supply.

Prime Movers for Industrial Plants.—There is a choice before the manufacturer installing his own plant of four principal prime movers; that is, there are four if we omit the exhaust steam turbine, which can only be regarded as a prime mover in combination with some other steam engine or engines. These four are :—

1. The steam turbine.
2. The reciprocating steam engine, vertical or horizontal, with double or triple expansion.
3. Suction-gas engine.
4. Diesel oil engine.

Steam Engines.—The prime mover which finds the most favour among manufacturers is undoubtedly the steam engine. This is not surprising when one remembers that there are many mill engines running to-day which have performed their tasks well-nigh perfectly for years on end, and so have planted in the minds of their owners a deep-seated and natural prejudice in favour of steam. One must therefore be prepared to show a very convincing record of reliability

and economy in the prime mover which one proposes to install for electrical generation, and this is not altogether an easy matter with new types of engines.

It may be taken in general that the reliability of the horizontal slow-speed and vertical high-speed engine, either simple or compound, will pass unquestioned in most industrial quarters; the triple-expansion high-speed vertical engine and the steam turbine come next, with the balance certainly in favour of the reciprocating engine. Then follow the debatable types such as the producer- or suction-gas engine, and the Diesel oil engine.

It will generally be found that a mill-owner would sacrifice a little —a very little—in economy to obtain as nearly as possible absolute reliability, and hence for powers under 1,000 k.w. the reeiprocating engine wins most often on the score of reliability. Under 500 k.w. it undoubtedly wins also on the score of economy, while over 1,000 k.w. the turbine is the victor.

In other industries where a large amount of steam is required for boiling, warming, drying, or other purposes, it rarely pays to run a turbine condensing, with a separate live steam supply for calorific purposes. In such cases we must revert again to the reciprocating non-condensing engine, whose exhaust steam can be conveniently used for manufacturing or other purposes as required. Any opportunity for advantageously installing an exhaust-steam turbine as mentioned earlier in the paper will naturally be seized and acted upon.

Considering now in brief detail the popular reciprocating engine, we may proceed to note the choice of type available. The selection of type will (or may) depend upon :—

1. The boiler pressure available from an existing plant.
2. The boiler pressure necessary or desirable for manufacturing purposes.
3. Whether the engine is to run condensing or non-condensing.
4. The probable relation of the average to the maximum load.
5. The possibility of overloads.
6. Capital available.
7. Space available.

The last two considerations generally put the horizontal engine out of court, and at any rate it is rarely considered in connection with factory work, the vertical high-speed engine being nearly always adopted.

Each industry demands different treatment in the selection of the type most suitable, but the factor with the greatest influence on choice is naturally that of power required. In the majority of works where vertical engines are installed, the demand will be somewhere between 100 H.P. and 600 H.P., and a boiler pressure somewhere between 60 lbs. and 160 lbs. will usually be available or suitable. Under these conditions one would generally install a 2-crank compound engine. These engines have few parts to keep in order, the economy is good, and the first cost low; the pressure is not high enough, moreover, for

triple expansion. For powers above 600 H.P. and where the steam pressure is too low for a triple-expansion engine, the 3-cylinder compound engine, having one high and two low-pressure cylinders, is the most suitable. Where a good pressure of 160–200 lbs. is available, and where an engine of at least 250 H.P. is required, it will be advisable to put in a triple-expansion 3-cylinder engine. Given a factory plant to lay out *de novo*, one might safely select in the majority of cases a medium boiler pressure of, say, 160 lbs. and a 2- or 3-cylinder high- and low-pressure compound engine. This means a plant of moderate first cost, although if more money be spent, greater economy can be obtained with a boiler pressure of, say, 200 lbs. and a triple-expansion engine.

Suction Gas Engines.—The subject of producer-gas engines has received a great deal of attention of late years, and references are given in this paper to sources* where full information as to the details of working, both mechanical and chemical, may be found.

The suction gas plant can only find favour with factory owners and others by a proof of very decided economy over other types, as certainly the average individual with a mill to drive will prefer the steam engine on the score of its greater simplicity and less first cost. Against the advantage of probable cheaper running cost one must offset in the case of the gas plant its high first cost, its inability to support overloads, the great amount of cooling and cleaning water required, and the nauseous character of the effluence from the scrubbers. There is very little saving in buildings, if any at all, as the regulations for factories require a separate building for the producers.

The gas plant will, however, be able to show considerable economical advantage in a station where there is much standing-by. Very little stoking is needed to keep the fires going sufficiently to enable gas to be produced when desired in a few minutes. This advantage is not likely to have much scope with isolated factory plants, however, as the essence of the success of such plants lies in their having a good running load factor and no standing-by. If these conditions do not exist, then it will be better in almost any circumstances to invite a supply from a power company.

The basis of argument in favour of the gas plant therefore consists in the saving in running which it promises to effect. There is some difficulty in obtaining reliable data as to the running costs of these plants, and when the data are really reliable they do not appear to be very favourable. However, with every wish to do justice to this type of plant, the author will reproduce first some figures which were given by Mr. P. W. Robson before the British Association Meeting in September, 1908, relating to power costs with suction gas engines.† These are given in Table V. Costs are here given for gas plants

* *E.g.*, "Note on Suction Producer Plant," by A. E. Porte, *Journal of the Institution of Electrical Engineers*, vol. 38, p. 697, 1907. "Gas Power," by J. E. Dowson; also *Journal of the Institution of Electrical Engineers*, vol. 33, p. 304, 1904.

† See *Electrical Review*, vol. 63, p. 446. "Production of Cheap Power by Suction-Gas Plants," by P. W. Robson.

TABLE V.*

Total Costs per Unit with Suction Gas Plants.

		Cement Works.	Weaving Shed.	Small Factory.
Particulars of load ...	Size of installation	450 H.P.	300 H.P.	20 H.P.
	Average working load	360 "	220 "	7·8 "
	Total B.H.P.-hours per annum	2,726,000	610,500	21,200
Capital outlay ...	Initial total cost of installation, including foundations	£4,230	£2,640	£250
		£ s. d.	£ s. d.	£ s. d.
Total annual running costs ...	Interest and depreciation at 10 per cent.	423 0 0	264 0 0	25 0 0
	Repairs and sundries	50 0 0	30 0 0	3 10 0
	Fuel at 20s. per ton	1,298 4 8	135 4 2	15 11 0
	Oil	135 3 10	10 0 0	2 0 0
	Water (taken from canal in Cases I. and II.) ...	—	—	7 5 0
	Attendance	423 17 4	135 0 0	12 10 0
	Total	2,330 15 10	574 4 2	65 16 0
Total costs per unit ...	Total cost per B.H.P.-hour	0·205d.	0·225d.	0·745d.
	Total cost per unit, taking dynamo efficiency = 0·85	0·324d.	0·365d.	1·175d.

* Figures quoted from paper on "Production of Cheap Power by Suction Gas Plants," read by P. W. Robson before British Association, September, 1908.

actually at work in a cement works, a weaving shed, and a small factory. The influence of load factor is very evident. The cement works has much the heaviest load, the power demand in this industry being very great and the load factor high. The running charges in this case swamp the capital charges, but on the other hand, the capital charges on the small factory plant completely outbalance the running charges, and the cost per unit is nearly three times as high. It is very doubtful if a suction-gas plant would ever be successful economically with a load factor of less than 15 per cent., due to the heavy charges for interest and depreciation.

The serious charge for water on the small plant is also interesting, being equal to half the total fuel cost, and illustrating one of the drawbacks to suction gas plant. At the same time the figure of less than 1¼d. per unit for so small a plant as 20 H.P. is remarkably good, and may give more food for thought to supply authorities.

TABLE VI.

Running Costs of Suction Gas Plant at Letchworth.

Particulars of running, December, 1909:—

Cost of coal per ton	36s. 8d.
Cost of water per 1,000 gallons...	1s.
Cost of oil per gallon	2s.
Coal consumed in lbs.	22,368
Coal used per unit in lbs....	1·68
Water used per unit in gallons	4·96
Oil used in gallons	9·00
Units generated	13,290
Cost of coal per unit	0·329d.
Cost of water per unit	0·059d.
Cost of oil per unit	0·016d.
Wages, per unit	0·336d.

Total works cost per unit, 0·740d.

Turning now to figures which the author can more easily vouch for, Table VI. gives the running costs of the suction-gas power station at Letchworth, for which figures I am indebted to the kindness of the consulting engineers, Messrs. Swinburne, O'Gorman, Baillie, and Dobree.

The plant consists of two 100-H.P. Campbell producer-gas engines, and a 300-ampere-hour battery. This station is at present running upon a very low load factor, and the costs per unit will necessarily be much less when more current is supplied.* It is not fair to regard these figures as the best of which the plant is capable, and capital charges have not been added, as the load factor is so poor. At Letchworth

* The costs have since been reduced from 0·740d. to 0·701d.

a supply of electricity was regarded as a necessary advertisement, and the station was not expected to bear a profit in its early years. Capital was also strictly limited, so that it will be seen that the difficult and variant conditions were adequately met by the suction gas plant.

To sum up, then, it may be stated that it may very well be advantageous to install suction gas engines :—

1. Provided that there is a large supply of water close at hand and costing very little (as a canal).
2. If the running and the annual load factors are both high.
3. If much standing-by is necessary.

Even though the running load factor were high these engines should certainly not be put in on a very low annual load factor, nor in cases where overloads more than 10 per cent. may be expected.

Diesel Oil Engines.—The Diesel high-speed vertical oil engine is perhaps the most recent of the medium power prime movers to be put forward for factory work. As is well known, this engine differs from ordinary types of internal combustion engines mainly in the fact that the oil vapour is ignited by a heated charge of air under intense compression in the cylinder head, and consequently no external source of ignition is required. This appears to render the engine remarkably simple and likely to prove independent of skilled attention in running. But the writer is informed on good authority that without something more than the attention which a driver accustomed to steam engines is likely to bestow upon it, the Diesel engine does not prove economical. It requires, in fact, highly skilled labour to run it successfully, and this imposes a serious restriction upon its use, since the ordinary "handy man" is not sufficient. Then the first cost of a Diesel oil engine plant is undoubtedly very much higher than that of either a steam or suction-gas plant, and this, of course, has a markedly unsatisfactory effect upon the total cost where the load factor is low.

The question whether it will be advisable to install a Diesel engine will turn upon the following considerations :—

1. Price of coal delivered.
2. Price of fuel delivered.
3. Load factor (annual), and less so (running).
4. Capital cost.

The relative costs of coal and oil will, of course, decide the question as to which has the advantage in fuel costs, and it appears that oil needs to be five times as dear as coal before it pays, as regards fuel costs, to substitute the steam engine for the oil engine. Assuming, however, that the saving in fuel cost is to balance the extra capital cost of the Diesel engine, it would be necessary to obtain the oil fuel at only 3½ to 4 times the cost of the coal. As it is not at all safe to

reckon on obtaining the oil delivered at less than, say, 58s. a ton, and as coal in industrial districts can very well be obtained at 12s. 6d. a ton or less, it is seen that the economy of the Diesel engine will be under average conditions rather at the mercy of the price of oil, which at present shows frequent inclination towards violent fluctuations.

It may be taken, then, that the reasons why the great claims of this engine do not lead to its more frequent installation are :—

1. Uncertainty as to price of oil.
2. High capital cost.
3. Need of more skilled labour.

The first two considerations in particular render it a very risky matter to recommend a Diesel engine for factory work, and they find a field rather for small lighting stations situated in country districts where coal is dear both to buy and to cart.

TABLE VII.

Running Costs of Diesel Plants.

Plant.	Kilowatts Installed.	Annual Load Factor.	Units per Annum.	Fuel Cost per Ton.	Works Cost per Unit.				Total Cost per Unit Generated.
					Fuel.	Oil, Water, and Stores.	Wages.	Repairs and Maintenance.	
		Per Cent.		s. d.					
Small central lighting station (summer load) ...	Two 100-k.w. sets	16	—	53 11	0·193	0·028	0·139	0·035	0·395
Same station (winter load)	Two 100-k.w. sets	16	—	68 4	0·245	0·027	0·310	0·067	0·645
Factory generating plant	160-k.w.	45	270,940	—	0·270	0·123	0·332	—	0·725

I am indebted to Messrs. Handcock and Dykes for some valuable figures as to the running cost of certain Diesel oil engine stations, and these results are set forth in Table VII. Running costs only are given.

The wide disparity in the purchase price of oil during the year will be noticed, and the distressing effect which this must have upon the owner of a plant can be judged.

This plant feeds a lighting network, but as this paper deals primarily with plants for industrial purposes, I append further figures in the table, for which I am again indebted to Messrs. Handcock and Dykes, showing the running cost of a plant installed for driving a factory. Other costs are given in Table I.

Dynamos.—The choice of type of dynamo is not a matter where many considerations count. Unless the load is subject to frequent variations the shunt-wound generator will give satisfactory results, and requires a switchboard slightly simpler than does a compound-wound machine. Where the load fluctuates violently, however, or where office or house lighting is to be provided, the compound-wound type must be adopted. Equalising connections are then advisable between the machines if more than one is installed.

Switchboard.—It is most important to keep the switchboard as simple as possible. Overload circuit breakers, for instance, are a doubtfully beneficent complication. There must be a reverse-current circuit breaker on each machine, of course, to provide for such contingencies as failing fields, careless switching, etc., and there should be an overload circuit breaker to each main feeder. It is most important in industrial work that the power should not be cut off suddenly, else all the belts come to a standstill on the fast pulleys, and there will be a succession of troubles in starting those motors which are intended to start up on a loose pulley. Thus it is as well to confine any stoppage to as small a section of the plant as possible, omitting the generator overload circuit breakers for this purpose. If fitted, they should have liberally set time-limit relays to retard their opening of the circuit. For a similar reason it is as well to split up the supply among a larger number of feeders than may be absolutely necessary. The switchboard instruments require no comments, except that they should be as few as possible, and be possessed of something more, if obtainable cheaply, than the usual clearness of figuring.

Capacity of Generators and Motors.—It may be taken as certain that the generating plant in a factory will never have the same capacity as that represented by the total horse-power of all the motors, etc., to be supplied from it. The exact relation will depend upon the diversity factor among the machines, upon the load factor of each individual machine, and upon the extent to which the machines are grouped or individually driven. Table VIII. shows how the capacity of generating plant has worked out in a number of different works where electrical plant has been installed, and it will be seen that the size varies from 20 per cent. of the maximum possible power in the case of a bleach and print works to 79·5 per cent. of the same in the case of a weaving shed.

With the total capacity of the generating plant decided upon, there remains the question whether it will be advisable to vest it in one set only or in two or three. It appears to be the best plan to install three sets each of half the average generating load, as with this combination the plant can be run economically at practically any load. A very small set generally driven by gas or oil is sometimes provided of perhaps $\frac{1}{10}$ the capacity of a main set for use to provide occasional trivial loads, such as a small night-lighting demand, which would be serious had it to be met by the main engine. It is not advisable to make the small set of a larger capacity if the outside supply is the

TABLE VIII.

Relation between Capacities of Generators and Motors and Load Factor.

Nature of Works.	Generators Installed.	1. Total Capacity of Generators Installed.	2. Capacity of Generators usually on Load.	3. Total Horse-power of Motors Supplied.	Ratio 1 : 3.	Ratio 2 : 3.	Running Load Factor.
		Kilowatts.	Kilowatts.	Horse-power.	Per Cent.	Per Cent.	Per Cent.
Shipyard and engine works...	Two 336-k.w. sets...	672	336	1,000	90·0	45·0	42·6
Engineering and steel works	Eleven sets of various capacities	2,715	—	5,804	62·8	Average 30·0	43·1
Paper-mill	One 500-k.w. set	500	500	990	67·0	67·0	70·0
Bleach and print works ...	Three 150-k.w. sets	450	300	1,000	60·3	40·2	45·0
Weaving-shed...	One 415-k.w. set... ... ... One 150-k.w. set...	565	415	700	108·0	79·5	90·0
Colliery...	One 1,500-k.w. set ... ... Two 750-k.w. sets	3,000	1,500	6,000	67·2	33·6	37·0

stand-by, as should the load by any chance assume decent proportions one could come on the mains for it until a satisfactory load for one main engine was reached.

Voltage and Current.—In the author's opinion the 3-phase alternating current should always be adopted, unless there are very strong reasons against it. For all heavy work, such as one may describe as a "steady grind," the induction motor with short-circuited rotor appears to be by far the best suited. It becomes advisable, if electrical is to be substituted for mechanical transmission of power to large single machines requiring a large input, to raise the voltage very considerably—say to two or three thousand—in order to keep down the cost of the cables required. This cannot be done conveniently with continuous current, but it is a simple matter with alternating current, and it seems to the author that high-pressure current with proper protection will in the future be distributed about works of certain kinds much more freely than has been the case up to the present.

For certain industries, such as mining and textile manufactures, 3-phase current is becoming standardised for well-known reasons; and on the other hand, in works such as engineering shops with many machine tools requiring individual variable-speed drive and where much work is done by overhead cranes, continuous current is adopted with equal unanimity.

Where there is no reason for choosing definitely either continuous current or alternating current, the author expects to see dual generation —high-tension alternating current and low-tension continuous current —in the large works which are likely to be electrified in the years before us. There is no reason to contemplate parallel and consequently wasteful distributing power lines under these circumstances, as the sections of a large works requiring one or the other species of current are usually quite distinct and can be fed accordingly. It would certainly mean a separate distribution for lighting purposes in those portions of the works using alternating current, but this would not amount to a large proportion of the whole and would not be wholly a disadvantage; moreover there would always be the possibility of inserting a transformer if the lighting load in any section were sufficient to warrant it.

Where, however, continuous current is adopted, a valuable aid enters the field in the shape of a battery, and a secondary battery of quite small proportions may prove very valuable in such works as engineering shops where the load factor is not particularly good; and without having any figures to offer on the point the author is of opinion that a moderate sized battery would certainly compensate in improved running cost for its prudent purchase in all works where the load factor is poor.

Country House Plants, etc.—As there is a constantly open field for the installation of small electric light plants in country houses, institutions, etc., a table of running costs under average conditions of country house plants may be of interest. Such costs are given in Table IX., relating in each case to oil engine plants.

TABLE IX.

Running Costs of small Oil Engine Plants (5 to 10 H.P.) for Country House Lighting.

Size of Installation (25-watt Lights).	Units per Annum.	Oil used per annum (in Gallons).	Oil used per Unit in Pints).	Oil used per Light per Annum (in Pints).	Units per Light per Annum.	Cost of Fuel per Unit (in Pence).	Cost of Fuel per Light per Annum (in Pence).	Remarks.
50	375	100	2·72	16·0	7·50	1·76	13·2	50-volt tantalum lamps; figures based on 1 year and 3½ months of winter.
70	360	120	2·67	13·7	5·10	1·74	8·9	Engine also used for pumping.
60	260	No exact record	No exact record	About 12·0	4·30	2·28	9·9	Engine also used for pumping. Oil consumption deduced from known facts.
140	500	260	4·15	15·0	3·60	2·70	9·7	Private school.
150	565	242	3·50	14·0	3·75	2·65	9·9	

In conclusion, I beg to express my very sincere thanks to Messrs. Swinburne, O'Gorman, Baillie, and Dobree, for their kindness in giving me the figures relating to Letchworth power station; to Messrs. Handcock and Dykes, for those relating to Diesel plants; to Mr. James Miller, of Rugby, for the costs concerning a colliery plant; and to Messrs. Tyler and Freeman, of Blackfriars, for permission to reproduce some of the information contained in the paper.

THE THEORY AND DESIGN OF CURRENT TRANSFORMERS.

By ARTHUR P. YOUNG, Student.

(*Abstract of Paper read before the Students' Section in London, April* 13, 1910.)

The object of the present paper is to present in a concise form the complete theory of the current transformer, showing how the two essential characteristics—viz., current ratio and phase displacement between primary and secondary currents—are affected by the factors entering into the design, and also by the variable factors likely to be met with in practice, such as frequency and secondary load. I have constructed a number of curves which are quite general in their application in the case of transformers built up with cores of "Stalloy" punchings, and in each case the range of the induction in the core is assumed to be from 0 to $B_{max.} = 1,400$ lines per square centimetre. It will be perceived that this range is very low, but for a good design the flux density in the core at full load should not exceed this figure, and there is no doubt that there are numbers of current transformers on the market in which the maximum value of the flux density in the core at full load is even less than 1,000 lines per square centimetre. I have chosen "Stalloy" iron as a basis for my calculations because it is the ideal iron to use for current transformers, possessing as it does a small core loss and high permeability at very low inductions. I am aware that there are other high-resistance "alloy" irons on the market, but know of at least one large firm making current transformers who have adopted this brand of iron, and believe that most other makers have done the same.

The Function of the Current Transformer.—When we have to measure an alternating current greater than, say, 100 amperes, it not only becomes difficult to construct an instrument to carry the whole of this current, but further, in the case of a wattmeter, serious errors will arise, due to the eddy currents set up in the conductors shifting the phase of the current flux so that on inductive loads the tendency will be for the wattmeter to read low. This effect, of course, could be overcome to some extent by employing laminated conductors, but even then, for currents above 300 or 400 amperes, the practical problem of building such instruments would be much more difficult than in the case where a small current winding is employed. Further, in the case of high-tension currents, it is impracticable to connect the instrument

direct on the high-tension circuit, because not only would the question of insulation present difficulties, but it would also become impossible for any one to make any tests or adjustments on the instrument when it was "live," which has to be done frequently in actual practice. For these reasons it becomes necessary to use current transformers in cases where we have to measure a current greater than from 100 to 200 amperes —depending on what type of instrument is employed—and in all cases of high-tension currents irrespective of the amperage. Not only does the field of usefulness of the current transformer apply to all classes of indicating, integrating, and recording instruments, but it also extends to the case of relay and trip coils, these invariably being energised in this way, the usual practice being to operate the necessary instrument and relay coils from the secondary of one transformer, which procedure is perfectly satisfactory provided the transformer is designed to give accurate results when so loaded. It is therefore apparent that the current transformer has three functions :—

1. To give a secondary current which bears a known and constant ratio to the primary current.
2. To give a secondary current which is exactly opposite in phase to the primary current.
3. To provide effective insulation between the primary and secondary windings.

Functions 1 and 2 are, of course, ideal, because, as will be shown later, the ratio of primary to secondary current is dependent to a slight extent on the value of the primary current, and it is—speaking generally —impossible to obtain exactly 180° phase displacement between primary and secondary currents, the discrepancy, although slight, being also dependent on the value of the primary current.

It is thus seen that the use of a current transformer on an alternating-current circuit is analogous to some extent to the use of a "shunt" on a direct-current circuit, only in the latter case there is no question of insulation or phase displacement, and the current ratio, simply being dependent on the resistances of the two branches, is a constant quantity and independent of the current through the shunt, provided these resistances do not change.

The Complete Mathematical Theory.—If we take an iron core wound with two coils and pass an alternating current of known value through one of them (primary), we shall find that on short-circuiting the other winding (secondary), through an ammeter, the instrument will indicate a current, the ratio of which to the primary current equals the ratio of the primary turns to the secondary turns very approximately. That is, if we assume that—

$$
\begin{aligned}
\text{Primary current} &= C_1, \\
\text{Primary turns} &= S_1, \\
\text{Secondary current} &= C_2, \\
\text{Secondary turns} &= S_2,
\end{aligned}
$$

then we have approximately—

$$\frac{C_1}{C_2} = \frac{S_2}{S_1},$$

or—

$$C_1 S_1 = C_2 S_2.$$

The above relationship represents the ideal case, in which we have the primary ampere-turns equal to the secondary ampere-turns, and this could only happen if there was no magnetic leakage between the two windings, and further, no current was required to overcome the losses in, and magnetise, the iron core. If such were the

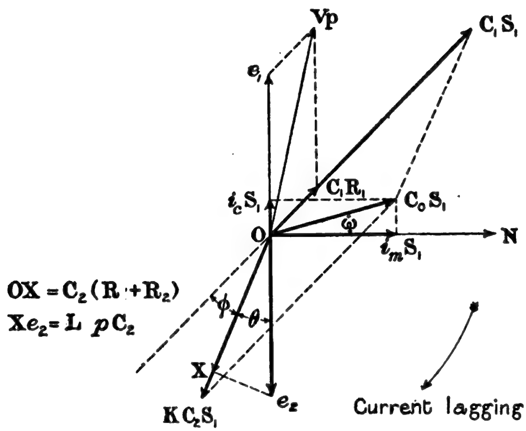

FIG. 1.

case, it is easy to see that the current ratio would be constant and equal to $\frac{S_2}{S_1}$ for all values of the primary current C_1, and further, the secondary current would be in direct opposition in phase to the primary current. That is, we should have a perfect current transformer fulfilling conditions 1 and 2 enumerated above.

Unfortunately such a result cannot be realised in practice, because a component part of the primary current has to compensate for the core loss and magnetising currents, and it is difficult to avoid slight magnetic leakage between the two windings. For the purpose of our investigation we will assume, however, that there is no magnetic leakage between the two windings, which assumption is, to all practical purposes, quite correct in cases where the core is built up of ring punchings and the two windings uniformly distributed over the whole surface, one being wound on the top of the other.

Taking the general case in which the load on the secondary circuit

is inductive, the condition of affairs is represented vectorially in Fig. 1. We assume that—

$i_m S_1$ = Magnetising ampere-turns in phase with the resultant flux N.

$i_c S_1$ = Core loss ampere-turns leading in phase by 90° the magnetising ampere-turns $i_m S_1$.

$C_0 S_1$ = Resultant of $i_m S_1$ and $i_c S_1$.

ω = Phase displacement between $C_0 S_1$ and $i_m S_1$.

e_1 = Induced voltage in primary due to flux N.

R_1 = Resistance of primary.

V_P = Voltage across primary. Resultant of e_1 and $C_1 R_1$.

e_2 = Induced voltage in secondary due to flux N. This is equal and opposite in phase to e_1.

R_2 = Resistance of secondary.

R = Resistance of secondary load.

L = Inductance of secondary load.

$C_2 (R + R_2)$ = Ohmic drop in secondary.

f = Frequency ($p = 2\pi f$).

$L p C_2$ = Reactance drop in secondary. This is at right angles to $C_2 (R + R_2)$, and the resultant of these two vectors is e_2.

θ = Phase displacement between C_2 and e_2.

ϕ = Effective phase displacement between C_1 and C_2. That is, with reference to the primary, the secondary current is equivalent to a current equal to C_2, and *leading* the primary current C_1 by a small angle ϕ.

K = Theoretical ratio $= \dfrac{S_2}{S_1}$.

The vector $K C_2 S_1$ is obviously equal to $C_2 S_2$, and is therefore equal to the secondary ampere-turns. It is thus seen that the ampere-turns

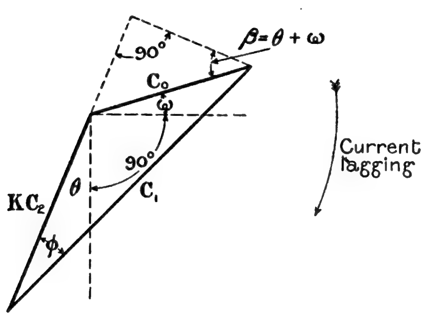

FIG. 2.

$C_0 S_1$ required to magnetise and overcome the losses in the iron core are the resultant of the primary and secondary ampere-turns. We can therefore readily deduce an expression for the current ratio $\dfrac{C_1}{C_2}$.

Referring to Fig. 2, the vectorial relationship between the primary and secondary currents is represented more clearly. We have then—

$$C_0^2 = C_1^2 + K^2 C_2^2 - 2 K C_1 C_2 \cos \phi,$$

also—

$$C_0^2 = C_1^2 - K^2 C_2^2 - 2 K C_0 C_2 \sin (\theta + \omega).$$

Subtracting we get—

$$2 K^2 C_2^2 = 2 K C_2 [C_1 \cos \phi - C_0 \sin (\theta + \omega)],$$

and thus—

$$K C_2 = C_1 \cos \phi - C_0 \sin (\theta + \omega).$$

Dividing through by C_1—

$$K \frac{C_2}{C_1} = \cos \phi - \frac{C_0}{C_1} \sin (\theta + \omega),$$

and calling—

$$\frac{C_1}{C_2} = K_A = \text{current ratio},$$

then—

$$\frac{K}{K_A} = \cos \phi - \frac{C_0}{C_1} \sin (\theta + \omega),$$

or—

$$K_A = \frac{K}{\cos \phi - \frac{C_0}{C_1} \sin (\theta + \omega)} \quad . \; . \; . \; . \; . \; . \; . \quad (1)$$

This is a fundamental equation giving us the current ratio for any value of the primary current, provided we know C_0, ϕ, θ, and ω. We can greatly simplify this equation by putting $\cos \phi = 1$, because in a well-designed transformer ϕ will not exceed 2° at one-twentieth of full load, and will be considerably less at the higher loads. The error introduced by this assumption will therefore not be greater than 0·06 per cent., which is negligible.

We therefore get—

$$K_A = \frac{K}{1 - \frac{C_0}{C_1} \sin (\theta + \omega)}.$$

Putting $\theta + \omega = \beta$, we can re-write this equation in the following form :—

$$K_A = \frac{C_1 S_1}{C_1 S_1 - C_0 S_1 \sin \beta} K \quad . \; . \; . \; . \; . \; . \; . \; . \quad (2)$$

This gives the current ratio in terms of the primary ampere-turns, and the component part of the resultant core loss and magnetising ampere-turns in phase with the secondary current—that is, $C_0 S_1 \sin \beta$.

We can also readily calculate ϕ. Referring again to Fig. 2, we see that—

$$\sin \phi = \frac{C_0 \cos \beta}{C_1} = \frac{C_0 S_1}{C_1 S_1} . \cos \beta.$$

As ϕ is so very small, we can put—

$$\phi = \sin \phi \text{ radians.}$$

$$\therefore \quad \phi = \frac{C_0 S_1}{C_1 S_1} \cos \beta \text{ radians} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (3)$$

This is a fundamental equation giving the effective phase displacement ϕ in terms of the primary ampere-turns, and the component of $C_0 S_1$ at right angles to the secondary current—that is, $C_0 S_1 \cos \beta$.

It is therefore apparent that before we can calculate either the current ratio or phase displacement corresponding to any given value of the primary ampere-turns, we must first of all know the values of

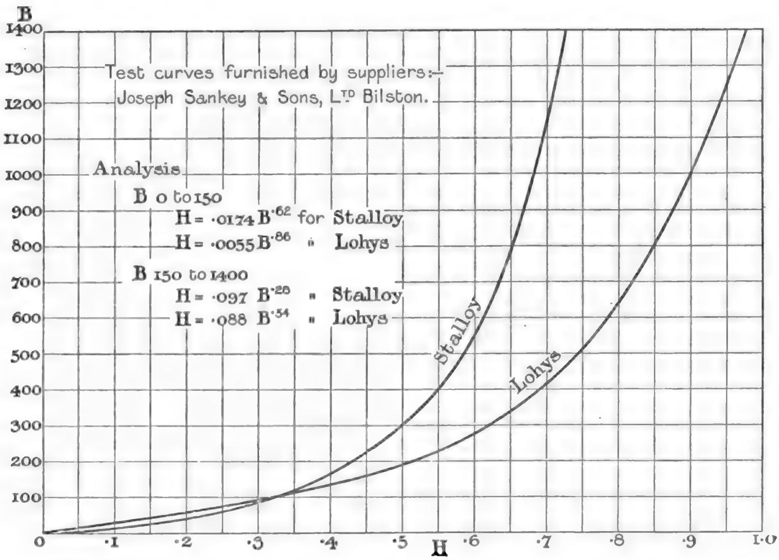

FIG. 3.

$C_0 S_1$ and β corresponding to the particular value of the primary current, or what amounts to the same thing, to the particular value of the induction in the core. We must therefore turn our attention to the core loss and permeability curves for the particular brand of iron we are using, corresponding to the limits of induction between which we are working.

Choosing "Stalloy" iron for reasons previously given, Fig. 3 shows the B-H curve for a range of B from 0 to 1,400 lines per square centimetre. For comparison the curve for "Lohys" iron is added, and the advantage of employing "Stalloy" iron at these low inductions is apparent. These test curves, as well as the core loss curves, were kindly sent to me by the suppliers of these brands of iron—Messrs.

Joseph Sankey & Sons, Ltd., Bilston. On investigation I find that approximate laws can be deduced for each curve, these being of the form $H = k\,B^n$. As a further approximation we can assume that the law changes at a value of $B = 150$ in each case, the constants k and n being different for the higher values of B between 150 and 1,400. For "Stalloy" iron the laws come out as follows:—

B's 0–150 ... ... $H = 0{\cdot}0174\,B^{0{\cdot}62}$ . . . . (4)

B's 150–1,400 ... ... $H = 0{\cdot}097\,B^{0{\cdot}28}$ . . . . (5)

Types of Current Transformers.—Fig 4 shows the type C, form G, current transformer manufactured by the British Thomson

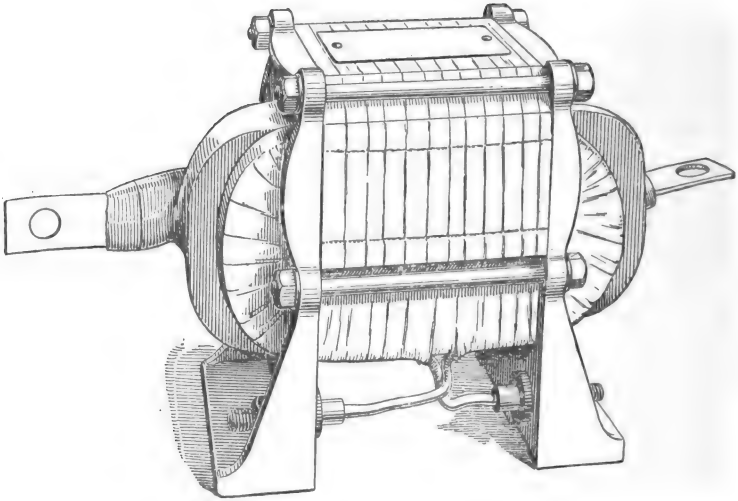

FIG. 4.

Houston Company, Ltd., of Rugby. It is made in capacities up to 500 amperes, and for voltages up to 7,000 volts to earth. Two sizes are manufactured, one size suitable for operating a single meter and a larger size having greater number of primary ampere-turns suitable for operating an ammeter, wattmeter, and heavy trip coil in series. As can be seen, the core is built up and former-made coils used.

The punchings overlap for a considerable distance so that the reluctance is small and the magnetising current thereby kept low.

The type C, form K_2, manufactured by the same firm, is of the bus-bar type, and is made in sizes up to 6,000 amperes, suitable for voltages varying up to 6,000 volts to earth. It is of particularly neat design, the primary consisting simply of a straight copper bar which passes through the centre of a core built up of ring-shaped punchings. The magnetic leakage in this type is therefore negligible.

All types of current transformers manufactured by this firm are tested for insulation at three times the maximum voltage for which they are designed to operate. "Stalloy" iron is employed throughout, the ratio characteristics for all types being nearly straight, and the phase error is also kept well within 0·5°, even down to very small loads.

Messrs. Everett Edgecumbe, Ltd., manufacture four models, the primary ampere-turns at full load varying from 300 in model I. to 1,600 in model IV. Model I. is designed for working a single ammeter or relay in cases where the instrument and transformer can be calibrated together: Model IV. is intended for use where extreme accuracy is required. The ratio is constant to within ¼ per cent. down to $\frac{1}{10}$ of

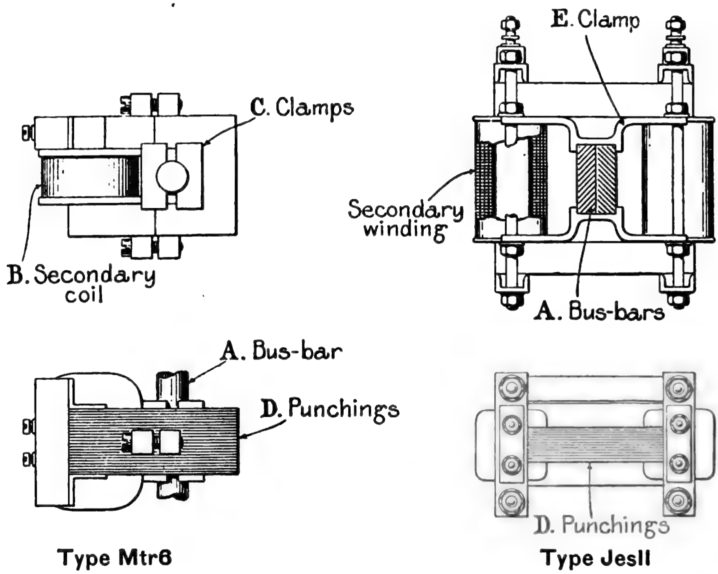

FIG. 5.

full load, or even less. The phase displacement is also kept very small, being about 0·5° at comparatively low loads. Their standard practice is to employ air insulated transformers up to 5,000 or 6,000 volts, and above that either oil or compound insulated transformers in cast-iron cases.

Siemens Bros. & Co., Ltd., manufacture a very large line of current transformers.* Two of their large current busbar types are shown in Fig. 5. The types Mtr6 has the core D made in two pieces which butt together, the two sections being held together by two screws. By removing one part of the core the transformer can be

* "Current Transformers for Measuring Instruments," *Electrical Review*, April 16, 1909. "Transformers for Use with Instruments," *Electrician*, March 12, 1909.

readily slipped on to the busbar A, which is gripped by the clamp C. The full load secondary current for this type is 1 ampere.

The type JesII, also shown in the figure, is suitable for currents varying from 250 to 6,000 amperes. The core is built up of rectangular-shaped punchings and carries a secondary coil on each limb, the two coils being coupled in series. The clamps E can be supplied in various shapes suitable for taking busbars of various sizes and sections. This type is designed to give 5 amperes in secondary at full load.

Current transformers manufactured by this firm up to 30,000 volts are tested at twice the working pressure, using approximately a sine wave. The ratio of each type is adjusted accurately to at least 1 per cent., and it is claimed that combined calibration of the transformers with instruments is generally not necessary.

COLLECTION OF CURRENT AT HIGH PERIPHERAL SPEEDS.

By P. J. COTTLE, B.Eng., and J. A. RUTHERFORD, B.Eng., Students.

(Abstract of Paper read before the Students' Section in London, January 19, 1910.)

Objects of Paper.—Very few results have been published on the behaviour of brushes collecting current at high peripheral speeds. To attempt to remedy this deficiency, experiments have been carried out on several distinct types of brush used in ordinary practice. The chief aim has been to obtain some idea of the relations governing :—

1. Voltage drop at contact, for both positive and negative brushes with varying current density in the brush.
2. Frictional losses.
3. Brush temperatures.

Apparatus Used.—The tests were performed on a specially balanced high carbon steel disc, 11 in. in diameter and 1¼ in. wide, shrunk on a shaft belt-driven by a 5-H.P. direct-current motor with a large speed regulation.

Both brushes were fixed at opposite ends of a diameter of the disc, and were arranged in box-type holders running on ball bearings in order to prevent errors due to friction in the measurement of brush pressure.

Pressure was applied to the brushes by means of levers connected together by spring balances, the tension of which could be varied at will.

Method of Conducting Experiments.—The rim was run up to the desired speed with the brush pressure set, and then the required current was passed between the brushes. Readings were taken when the temperature of the brushes, as indicated by the galvanometer, was constant. The time taken to attain a constant temperature varied, being about 20 minutes for an increase in current of 10 amperes, *i.e.*, an increase in current density of 40 amperes per square inch.

Experiments were conducted :—

1. By keeping speed and pressure constant and varying the current density ; reading positive and negative drops and temperatures.
2. Repeating similar observations for various values of pressure.
3. Varying the speed and going through the above process again.

Peripheral Speed in Feet per Minute.	Current Density in Amperes per Square Inch.	Voltage Drop.	Coefficient of Friction.	Voltage Drop.	Coefficient of Friction.	Voltage Drop.	Coefficient of Friction.
Type A		Pressure = 4 lbs. per Square Inch		Pressure = 8 lbs. per Square Inch.		Pressure = 16 lbs. per Square Inch.	
1,850	40	1·0		1·20		—	
	120	1·7	0·4	1·70	0·30	—	0·35
	200	2·4		2·40		—	
3,000	40	0·9		1·10		1·100	
	120	2·1	0·3	2·00	0·28	1·700	0·40
	200	—		2·20		2·100	
Type B							
1,850	40	0·2		0·15		0·010	
	120	0·6	0·2	0·18	0·04	0·015	0·20
	200	1·0		0·21		0·020	
6,000	40	2·0		0·80		0·040	
	120	violent	0·5	violent	0·35	0·100	0·40
	200	sparking		sparking		0·400	
Type C							
1,850	40	0·8		0·65		0·400	
	120	1·0	0·5	0·90	0·30	0·600	0·28
	200	1·1		1·10		0·700	
6,000	40	1·5		0·50		0·100	
	120	1·7	0·4	0·80	0·20	0·500	0·24
	200	3·5		1·00		0·600	
		Pressure = 8 lbs. per Square Inch.		Pressure = 12 lbs. per Square Inch.		Pressure = 16 lbs. per Square Inch.	
12,000	40	3·5		3·8		1·500	
	120	4·8	0·5	5·0	0·08	1·600	0·20
	200	5·1		5·0		2·300	
17,000	40	3·6		3·2		2·000	
	120	4·1	—	4·1	0·07	3·800	0·18
	200	4·3		4·6		6·000	
Type D		Pressure = 2 lbs. per Square Inch.		Pressure = 8 lbs. per Square Inch.		Pressure = 16 lbs. per Square Inch.	
1,850	40	1·2		1·2		1·600	
	120	1·4	0·5	1·3	0·30	1·200	0·08
	200	1·5		1·4		1·300	
4,000	40	1·4		1·3		0·750	
	120	1·7	0·5	1·5	0·15	1·000	0·40
	200	1·8		1·6		1·200	
		Pressure = 8 lbs. per per Square Inch.		Pressure = 12 lbs. per Square Inch.		Pressure = 16 lbs. per Square Inch.	
6,000	40	0·9		0·8		0·200	
	120	1·3	0·1	0·9	0·40	0·400	0·50
	200	1·4		1·3		0·500	

On the completion of the steel test, the disc was coated with copper electrolytically, and tests were carried out with one type of brush on this surface. When, however, a peripheral speed of a little above 6,000 ft. per minute was reached, the copper commenced to strip off.

At high speeds and small pressures trouble was experienced with the vibration necessarily associated with these speeds, and below a certain pressure the readings taken were useless, on account of the fluctuation due to the varying air-gap length between brush and rim.

Types of Brush Tested.—All brushes used were ½ in. by ½ in. by 1 in. long. They may be classified under four headings :—

Type A.—A cheap carbon brush, hard and brittle.
„ B.—A metallic brush, composed chiefly of copper, with admixture of graphite ; very hard and of low specific resistance.
„ C.—A soft high quality brush, composed chiefly of graphite mixed with a trace of copper.
„ D.—A high quality pure carbon brush, moderately soft.

The table opposite gives the average values of the voltage drop one may expect at the contact of brush and steel surface under various conditions.

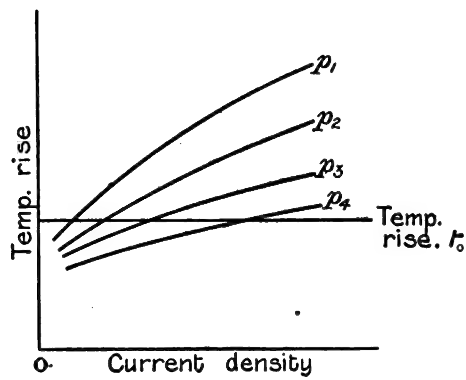

FIG. 1.

Economical Pressure and Current Density to Use at Turbo Speeds.—From the tests it appears that brush C is the only one which gave at all workable results above a speed of 6,000 ft. per minute. It was noticed that at higher current densities the electrical losses are quite comparable with the friction losses, and hence it may be more economical to run with a pressure considerably above that necessary to ensure sparkless running in order to decrease the electrical loss. But increase of pressure with this type of brush, as has been noted before, means a large increase in temperature, which effect must not be lost sight of. A rough method of obtaining the most economical values of pressure

and current density at any given speed, consistent with a specified temperature rise, is as follows:—

Assume a given speed n and a given temperature rise t_0. From the table of results plot temperature rise against current density for a series

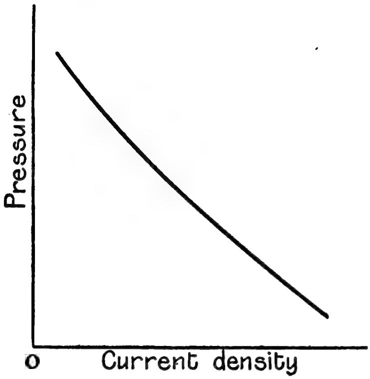

FIG. 2.

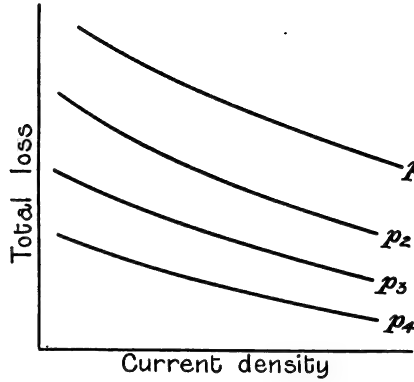

FIG. 3.

of pressures (see Fig. 1). Draw a constant temperature line for rise t_0. From this curve plot the values of pressure and current density for the given temperature rise (see Fig. 2).

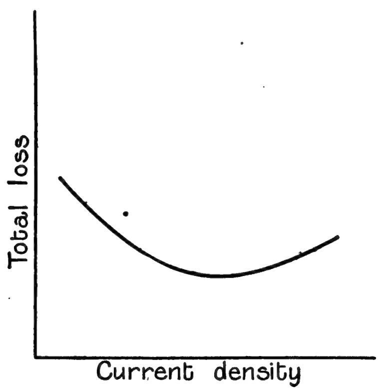

FIG. 4.

Now plot total loss against current density for various pressures, this giving Fig. 3. From this, for each value of current density take the value of pressure from Fig. 2, trace on Fig. 3, finding total loss for that value of pressure and current density.

Now plot this loss against current density and take the minimum point on this curve, this gives the most economical value of current

density, and tracing back to Fig. 2 we get the most economical pressure to use.

This method has been adopted for the following results, a very low temperature rise of 25° C. having been taken owing to the large radiating surface and heat capacity of the apparatus :—

Speed in Feet per Minute.	Pressure in lbs. per Square Inch.	Current Density in Amperes per Square Inch.	Surface Steel throughout.		
			Electric Loss.	Friction Loss.	Total Loss per Ampere Collected.
			Watts.	Watts.	Watts.
1,850	11·5	210	109	80	3·60
4,000	12·0	140	67	34	2·90
6,000	7·0	130	74	100	5·53
12,000	12·0	100	250	300	22·00
17,000	11·0	80	200	220	21·00

For types B and D the following results have been deduced :—

	Speed in Feet per Minute.	Pressure in lbs. per Square Inch.	Current Density in Amperes per Sq. Inch.
Type B ...	1,850	6	160
	6,000	12	160
	10,000	20	—
Type D ...	1,850	12	200
	4,000	12	160
	6,000	12	120

Advantages of Employing a High-current Density.—

1. Economy of first cost, both in brushes and running gear.
2. Better running owing to smaller number of brushes and so smaller length of collector surface.

The choice of pressure at high-current densities is influenced considerably by the tendency to spark, and also by the amount of wear of brushes and cost of replacement. This depends absolutely on condi-

tions of running, and, of course, no figures can be given, personal judgment having to be relied on.

Difference between (+) *and* (—) *Drops.*—In general, it may be said that the drop at the negative brush is higher than the drop at the positive brush.

This might be due to several causes :—

1. Thermoelectric effects.
2. Formation of compounds at surfaces of contact.

1. Unless very high temperatures obtain at the points of contact of brush and rim this first effect cannot have very much to do with the phenomenon. If the current is transferred from brush to rim through very minute arcs, not ordinarily visible, the voltage due to thermoelectric effects may rise to 100 millivolts, so giving a difference of 0·2 volt between the two drops.

Of course, if these local high temperatures do not occur, thermoelectric effects are negligibly small.

2. When current flows from carbon to steel there is a possibility that at a high temperature a carbide of iron might be formed on the steel surface, which would increase the contact resistance. This increase in resistance would be exceedingly small. Standing tests on brushes A and C indicate that speed has very little, if any, effect on the difference in drops. It only seemed to affect the total drop.

Experiments were tried with a pure copper brush on a copper surface, and in this case the drops were the same to within 1 millivolt, *i.e.*, between 5 and 10 per cent. difference.

From the above the authors are of opinion that the transference of electricity takes place through very minute gaseous zones which must exist between the two contact surfaces, the high temperatures of the arc being necessarily associated with this, thus giving rise to thermoelectric effects sufficient to cause the difference between the two drops.

THE HIGH-TENSION SPARK DISCHARGE IN AIR.

By Philip Kemp, M.Sc. Tech., and William Arthur Stephens, M.Sc. Tech., Students.

(Abstract of Paper read before the Students' Section at Manchester, January 18, 1910).

The apparatus used in the tests made by the authors consisted of a 3-phase 15-k.w. 250-volt 4-pole alternator, driven by a 400-volt motor. This machine was chosen on account of its excellent wave form, which gives an amplitude factor, *i.e.*, $V_{max.}/V_{r.m.s.}$, of 1·44. In studying the effect of wave-form, and for other purposes, a second alternator was arranged so that it could be alternatively connected up. This machine was a 3-phase 40-k.w. 250-volt 6-pole alternator, and was belt driven from a 220-volt 60-H.P. motor. This alternator had an amplitude factor of 1·60.

All the experiments conducted in connection with this paper were carried out with a frequency of 50, except where it is specially noted otherwise.

The supply from the alternator was brought to a Stillwell regulating transformer with a ratio of 2 : 1, the secondary of which was divided into 20 equal sections. Tappings were taken from this regulator secondary to the main transformer.

The main transformer was a 25-k.w. single-phase Westinghouse oil-cooled transformer with a ratio of 204 : 1. With this transformer it was possible to obtain pressures up to 120,000 volts. The secondary was divided into four coils which could be connected at will in series, series parallel, or parallel, giving ratios of 204 : 1, 102 : 1, and 51 : 1. A connection was also brought out from the middle point of the secondary for purposes of earthing when required.

The voltage was measured on the primary side of the main transformer by means of an Addenbrooke testing set, the voltmeter of which was of the electrostatic type. In connection with this set, multipliers of from one to five could be obtained by means of a resistance box.

The voltage recorded is the maximum voltage reached just before the spark passes, and consequently the transformer was then taking little more than its no-load current, for which condition the ratio of transformation was found to be 204: 1. The readings were further checked from time to time by placing across the secondary a Kelvin electrostatic voltmeter reading to 100,000 volts. This voltmeter was

calibrated on the lower part of its scale by placing the Addenbrooke set across the secondary side of the transformer, in parallel with the Kelvin electrostatic voltmeter.

The authors concluded, as the result of these tests, that it was perfectly justifiable to measure the voltage in the manner stated above.

Factors Affecting Discharge.

The sparking potential for a given sparking distance in air is influenced by the following factors:—

1. The shape of the electrodes.
2. The local conditions of the circuit.
3. The wave-form of the E.M.F. used.
4. The frequency of the E.M.F. used.
5. The rate of growth and steadiness of the E.M.F.
6. The physical condition of the air, viz.:—

    (*a*) Pressure.
    (*b*) Temperature.
    (*c*) Humidity.
    (*d*) Light.

The Shape of the Electrodes.—The shape of the electrodes plays a most important part in the determination of the sparking voltage for a given distance. The presence of sharp edges or anything in the nature of points reduces the sparking voltage enormously, so that on this account it is highly necessary to offer a good well-polished surface to the passage of the spark, as otherwise the readings obtained would be too low. For the purpose of obtaining such a surface the authors have found it advisable to amalgamate the surfaces of the electrodes before use, and subsequently to wipe them over from time to time with a cloth moistened with mercurous nitrate.

The shape of the electrodes largely determines the distribution of the electrostatic field, and the more intense this field becomes the lower is the potential which will cause a spark to pass. With pointed electrodes the field is much more intense in the neighbourhood of the points than would be the case with rounded electrodes, and thus it is found that the former give lower values for the sparking voltage than the latter would give for the same sparking distance.

The accompanying curves (see Fig. 1) illustrate very well the effect of shape of electrode on the sparking voltage for various air-gaps.

Curve I.—Electrodes—Needle Points.
" II.—Electrodes—Spheres 3·81 cm. diameter.
" III.—Electrodes—Parallel plates with rounded edges.
" IV.—Electrodes—Cylinders 1·9 cm. diameter with their axes at right angles.
" V.—Electrodes—Spheres 7·62 cm. diameter.

As is to be expected, the curve for needle-point electrodes is the lowest, owing to the intense field, and consequent intensification of ionisation around the points.

In the curve for parallel plates a curious "kink" is observed. As will be seen later, "kinks" of a similar nature will be found in connection with various other types of electrodes, and will be fully dealt with in another portion of the paper.

The curve for parallel plates gives lower values for sparking voltage than the curve for 7·62 cm. diameter spheres, which would appear somewhat peculiar, in view of the facts that the sparking voltage for a

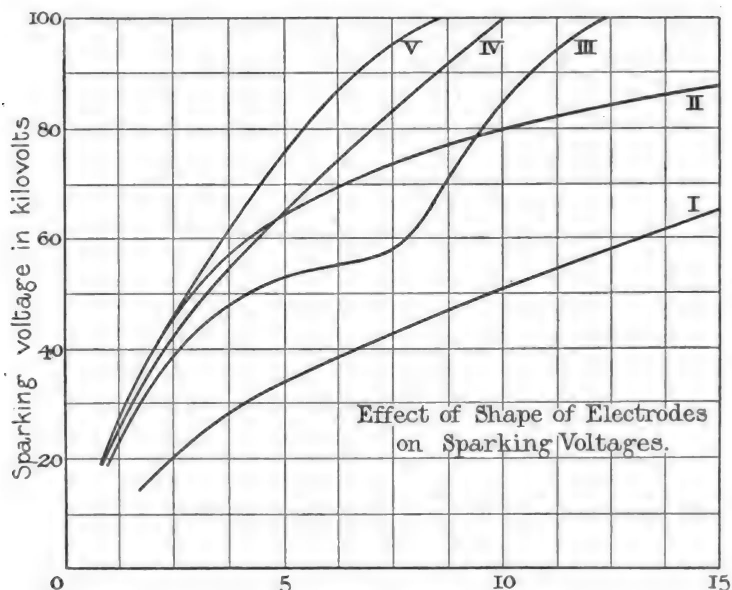

FIG. 1.

given gap increases as the diameter of the spherical electrodes increases, and that parallel plates may be regarded as spheres of infinite diameter. This reduction is attributed to the sharp curvature at the edges of the discs, in the neighbourhood of which the spark always passed. In general it will be found that when a spark passes from an electrode which has different radii of curvature at different portions of its surface, the spark always passes in the neighbourhood of the sharp curvature owing to the comparative intensity of the electrostatic field at this point. It is on this account that it is so difficult to obtain reliable readings with parallel plates since the spark passes at the edges where the field is not that due to a pair of parallel plates, but is distorted by their edges.

As a result we may roughly divide electrodes into three classes:—

1. Flat electrodes with rounded edges, and electrodes in the shape of spheres or portions of spheres.
2. Flat electrodes with sharp edges and other sharp-edged electrodes.
3. Pointed electrodes.

The Local Conditions of the Circuit.—For the purpose of studying the effect of the local conditions of the circuit a series of three experiments was performed, using a pair of 2·2 cm. diameter spheres as electrodes. The first test was performed with the spark-gap connected directly to the transformer secondary terminals, nothing else being connected thereto. The second test was performed with an auxiliary gap consisting of two 7·62 cm. diameter spheres at a distance of 10 cm. apart connected in parallel with the main spark-gap. A third test was conducted with two large choking coils connected one in each lead from the transformer secondary, in series with the main spark-gap, the whole system remaining balanced with respect to earth, the middle point of the transformer secondary being earthed. It was found that the effect of alteration of the local conditions of the circuit was to vary the position of the "kink" and the portion of the curve immediately following it. The effect of putting extra capacity in the circuit is to bring the "kink" down the curve and also to accentuate its magnitude. The inductance also has the effect of displacing the "kink" in the same direction and of slightly increasing its magnitude.

The Rate of Growth and Steadiness of the E.M.F. used.—The voltage required to spark across a particular air-gap is considerably smaller when the rate of growth of the voltage is great, than is the case when the voltage is applied gradually. For instance, when the voltage is applied suddenly by the closing of the main switch, the breakdown voltage is much smaller than when the voltage is slowly increased till breakdown occurs. It is exceedingly difficult to obtain consistent results for breakdown voltages with different rates of growth. For this reason all breakdown voltages should be measured in such a way that the voltage is applied so slowly as to produce no appreciable reduction of the breakdown voltage. Even if the voltage is steady, the length of time during which it is applied will affect the breakdown, which may occur when a high voltage is applied gradually or when a slightly lower voltage is applied continuously. Theoretically it should be possible to obtain a curve showing the relation between the breakdown voltage and the duration of its application. Unfortunately, however, we were unable to obtain consistent results for air, although we have been successful in obtaining time curves with solid dielectrics.

Another fact to be considered is that a sudden variation of the applied voltage (apart from the cyclical variation) may cause a discharge to take place at a lower value than would be the case with a perfectly steady voltage.

Physical Condition of the Air.—(*a*) *Pressure:* As the pressure of the air is diminished, the sparking voltage for a constant air-gap is also diminished, until a certain minimum value is reached. This value of the pressure of the air is known as the "critical pressure," and is approximately inversely proportional to the spark-length, whilst the minimum voltage is independent of the spark-length. On further decreasing the pressure of the air below the critical pressure, the voltage required to produce a spark across a given gap increases very rapidly, so that it is probable that it would be absolutely impossible to spark across a gap in a perfect vacuum. This at once follows from the ionisation theory, the absence of gaseous ions in a perfect vacuum accounting for the impossibility of a discharge taking place.

The effect of increasing the pressure of the gas is to increase its dielectric strength, it having been often stated that the latter is directly proportional to the former. It has recently been shown, however, by Mr. E. A. Watson * that this is only approximately true, and that such a statement only applies when the radius of curvature of the electrodes is indefinitely large.

(*b*) *Temperature.* — In accordance with the law enunciated by Paschen, the sparking voltage is directly proportional to the mass of gas between unit area of the electrodes. Now if the pressure is constant the mass in a given volume is inversely proportional to the absolute temperature; therefore for a given spark-length and fixed electrodes the sparking voltage would appear to be inversely proportional to the absolute temperature. This is in agreement with the ionic theory, since an increase of temperature means an increase of the mean free path of the ions, and hence a decrease of the sparking voltage.

From the above considerations it will be seen that any variation likely to take place during our experiments will not cause a greater error than 2 per cent., and hence can be neglected as being within the range of error in the observations.

(*c*) *Humidity.*—Throughout the range of our experiments with ordinary atmospheric conditions, the variation in the humidity is not sufficient to cause any appreciable variation in the sparking voltage at small distances, and therefore Dr. Russell's $R_{max.}$ is almost independent of any ordinary humidity, an increase of which, however, must tend towards a reduction in the sparking voltage. We have repeatedly observed that a variation in humidity affects the "kink," at least in magnitude; in fact, the effect is so marked that at high humidities it is exceedingly difficult to obtain a "kink" at all, the points lying on a smooth curve above the depression.

(*d*) *Light.*—At atmospheric pressure the light has little appreciable effect on the sparking voltage, but its effect may be observed by using rarefied gas. It has been shown by Warburg † that a greater voltage is

* *Journal of the Institution of Electrical Engineers*, vol. 43, p. 113, 1909.
† *Sitz. Akad. der Wissenschaften*, Berlin, xii., p. 223, 1896.

necessary to cause a breakdown in the light from an electric arc than in ordinary daylight. He has also shown that the chief effect of ultra-violet light is to diminish the "time lag," *i.e.*, the time interval between the application of the voltage and the passage of the spark, and that the effect on the sparking voltage is comparatively small.

Forms of Discharge: (*a*) *Corona.*—When a difference of potential is applied between two electrodes, luminous effects are sometimes produced. These luminous effects are known as coronæ, and we shall separate them into two divisions: (1) glow discharge which occurs at comparatively low voltage, and (2) brush discharge which occurs at a later stage and continues until breakdown occurs. In order to illustrate the above statements the following description of an experiment is appended. Two metal discs were placed, one on either side, about the centre of a sheet of plate glass about 20 in. square and ¼ in. thick, and a gradually increasing potential difference was applied to them. The first noticeable effect was a faint hissing noise at about 4,500 volts. This was probably the commencement of the glow discharge which, as yet, was invisible. When 5,000 volts was reached the glow became just visible, and at 7,500 volts the noise suddenly changed in character, crackling commencing. This is probably due to a brush discharge inside the corona. The corona did not completely surround the electrode until 13,000 volts was reached; a fact which is probably due to the decentralisation of the electrodes on the glass. At 18,000 volts short streamers were seen to shoot out from the discs into the surrounding air. These streamers correspond to what is known as the brush discharge. As the voltage was gradually increased, the glow and streamers increased in size, the latter becoming irregular. Occasionally a white "pilot" spark was seen to pass over the surface of the glass from one electrode to the other, and finally breakdown occurred at 67,500 volts. The glow discharge is usually of a light blue tint, whilst the streamers comprising the brush discharge are more of a bluish-violet colour. The pilot sparks are extremely vivid, so much so that attempts to photograph them frequently result in reversal. They are probably white or very pale blue, and are very actinic. When the breakdown occurs, the resulting arc is yellow, due to the particles of metal vapour which are torn from the electrodes.

(*b*) *Brush Discharge.*—If two electrodes which are enveloped in coronæ have the potential difference between them increased, the luminous appearance very often takes a characteristic form, which has been called the brush discharge. From the surfaces of the spheres appear short straight stems of considerable luminosity, which split up into numerous twig-like branches of inferior brilliancy and of a purplish-violet colour. These further subdivide into still smaller ramifications, which ultimately disappear in the air. This phenomenon is accompanied by a hissing sound altogether distinct from the short crack of the pilot spark. The pitch and character of this sound, which sometimes approaches that of a musical note, varies with the proximity of neighbouring conductors. It has also been found that the character

of the brush obtained varies with polarity, the negative brush keeping its form unchanged under considerable variation of influencing circumstances, whereas the form of the positive brush is more readily affected. The pitch of the sound is lower in the case of the negative brush, but the positive is of greater extent and brilliancy. With alternating potential the appearance of the luminous effects at each electrode also alternate.

(*c*) *Spark.*—At the ordinary atmospheric pressure the discharge between two spheres at a moderate distance apart takes the form of a brilliant, sharply defined streak of light. For small distances the spark

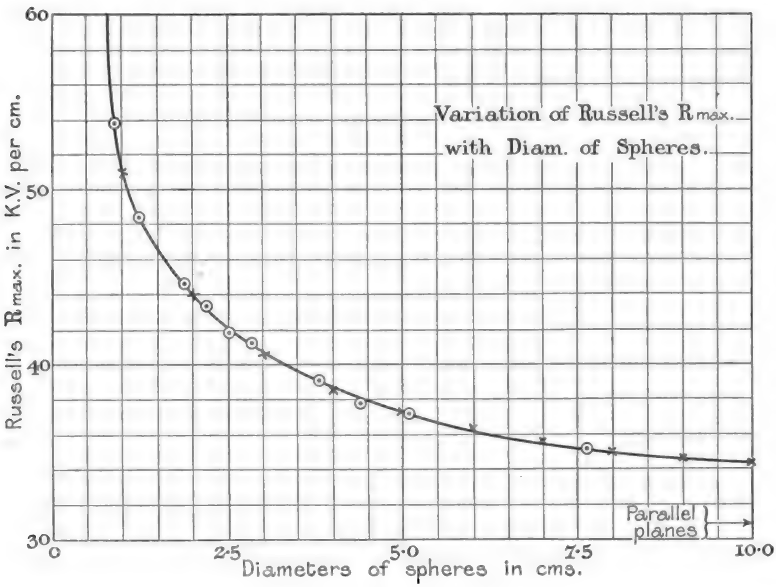

FIG. 2.

is more or less straight, and is thicker, or at least more brilliant, at the ends than in the middle. When the distance is considerably increased the spark assumes the characteristic zigzag form seen in forked lightning. It is probable that the spark is split up into branches, as is the case with direct pressure, but this, of course, cannot be seen without a rotating mirror owing to the rapidity of the alternations. The colour of the spark in air is bluish, but at the same time its great brilliancy gives an impression of whiteness. The duration of this form of discharge is exceedingly short, but it has the effect of tearing metallic particles from the electrodes, and by means of these the arc is established and maintained, even though the potential difference may fall considerably. The colour of this arc will obviously depend upon the material of the electrodes and the intervening medium.

Dielectric Strength of Air.—The measurement of the dielectric strength of air has engaged the attention of electrical engineers for some time, various experimenters having done work in this direction. In the majority of cases direct pressures have been used, whereas practically all commercial high-tension work is done with alternating current. C. P. Steinmetz * used several sizes of spherical electrodes in his experiments, which were conducted with alternating pressures. Dr. Russell † has used the results of these experiments to calculate by means of his formula the dielectric strength of air. It is chiefly on these results, and on those of Heydweiller and Algermissen with direct pressure, that he bases his value of 38 kilovolts per centimetre (approx.) for the dielectric strength of air under atmospheric conditions. It is noteworthy that the three experimenters above referred to have all used 2-in. or 5-cm. spheres in obtaining their results. Steinmetz, in addition, used smaller spheres, but from these results Dr. Russell obtained much higher values for his $R_{max.}$—*i.e.*, the dielectric strength of air. He neglected these results as he thought his formulæ might not apply to small spheres attached to cylindrical rods of appreciable size.

The actual mean values obtained by the authors in conjunction with Mr. Lustgarten are given in the following table, and also shown graphically in Fig. 2 :—

Diameter of Spherical Electrodes in Centimetres.	Value of $R_{max.}$ in Kilovolts per Centimetre.
0·9	53·8
1·25	48·4
1·90	44·6
2·20	43·3
2·54	41·8
2·86	41·2
3·81	39·0
4·40	37·5
5·08	37·1
7·62	35·2
Baille's results with parallel planes	30·8

It will be seen that the apparent values of $R_{max.}$ are much greater for the small spheres than for the large ones.

It is remarkable that, within the authors' knowledge, it has never been stated that these various values of $R_{max.}$ fall in a regular sequence as shown in Fig. 2. Not only so, but the values of $R_{max.}$ calculated from Baille's results, with parallel planes, afford striking confirmation of this fact, since the line representing this value is asymptotic to the curve. The crosses on the curve in Fig. 2 are obtained from the equation—

$$R_{max.} = 30{\cdot}8 + \frac{37{\cdot}5}{d + 0{\cdot}85}$$

where d is the diameter of the spheres in centimetres.

* *Transactions, American Institution of Electrical Engineers*, vol. 15, p. 281.
† *Phil. Mag.* (6), vol. 11, p. 247, 1906.

The most striking feature of breakdown voltage curves (see Fig. 3) is the peculiar "kink" or sudden increase in the breakdown voltage for a slight increase in the sparking distance, at one particular point. This sudden rise, under favourable conditions, may amount

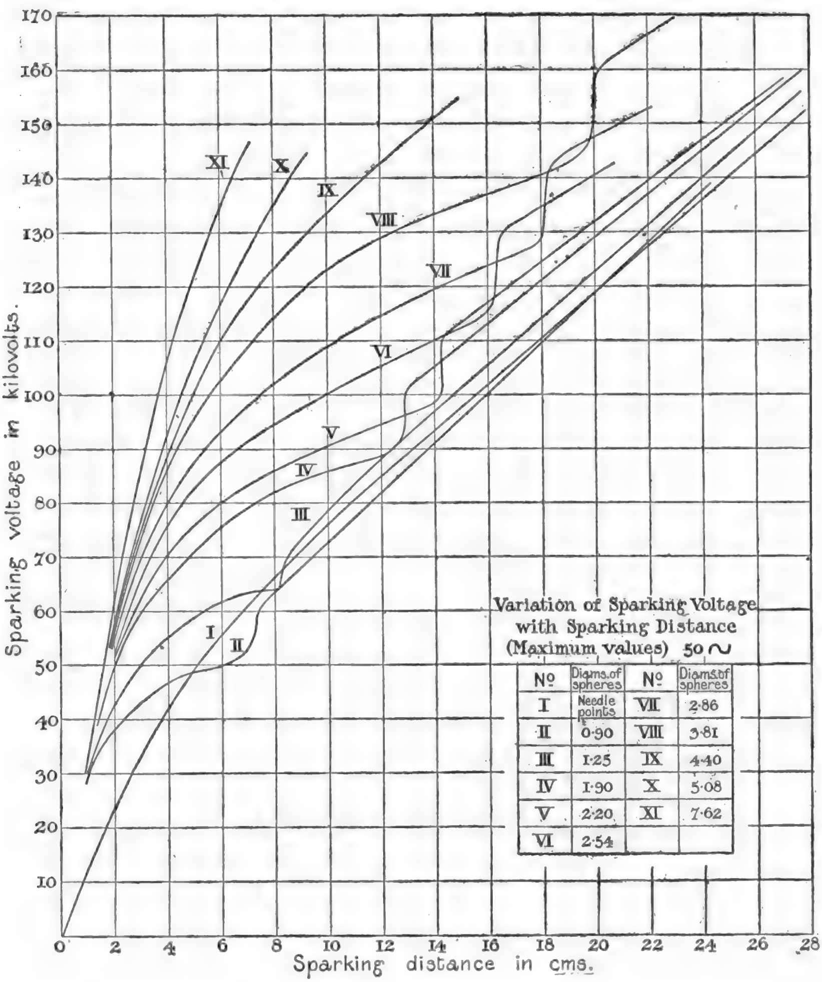

FIG. 3.

to as much as, or even more than, 50,000 volts. Omitting the downward bend and the subsequent sudden rise, it is possible to draw a smooth curve joining the lower and upper halves. At the point where this smooth curve and the actual one begin to diverge the first

indications of a glow were noticed. Further, when the sudden rise occurred, the noise due to the discharge was completely altered in character from a hissing to a crackling noise, a fact which points to the simultaneous appearance of a brush discharge. It would thus appear that the "kink" is due either to a change in the character of the discharge or to a change in the physical condition of the air.

It has recently been suggested that the sudden rise occurs at the same time as the appearance of the glow, but, in our experience, this is not so, the glow certainly appearing long before this stage is reached. It will be noticed from the curves in Fig. 3 that the ratio V/x, where V is the sparking voltage at the bottom of the "kink" and x the corresponding sparking distance, is constant. It will also be found that x/a, where a is the radius of the sphere, is approximately constant. Thus in the formula—

$$\text{electric field intensity} = \frac{\text{voltage}}{\text{distance}} \times f,$$

f is constant though incalculable due to the presence of coronæ, and

$$\frac{\text{voltage}}{\text{distance}} = (V/x)$$

s also constant, and it therefore follows that the electric intensity is the same at the bottom of all the "kinks." It will be found that this is fairly true for the tops as well. This again suggests that the "kink" is the effect of one of the two causes previously mentioned. The largest "kinks" are obtained by using different-sized electrodes; the greater the difference in size, the greater does the "kink" become. It is also a fact that the ideal conditions for a brush discharge are those in which a large and a small sphere are used as electrodes, and this would therefore appear to add additional evidence in favour of the above suggestions. Brush discharge, being the local break-down of air, will always occur at a definite electric intensity in that particular locality, and it may or may not relieve the strain on the other part of the gap. If it does not, then the spark will follow immediately on the brush discharge. If, on the other hand, it does relieve the remainder of the gap, the brush discharge will be formed and will continue. This means an absorption of energy to provide for the energy of the brush, and since the current is very small, may mean a considerable absorption of voltage. Below the "kink" brush discharge does not appear, and the discharge passes straight from the glow to the spark. Above the "kink" the conditions are such that brush discharge does appear, and consequently part of the applied voltage is absorbed in maintaining this brush. Hence the voltage required to break down the gap is increased by the voltage required to maintain the brush discharge. The above appears to form a very plausible explanation of the nature of the "kink."

Another theory which has been advanced states that the "kink" is due to resonance. In order to test this theory, it was thought advisable to determine what effect, if any, the frequency of supply

had upon the position of the "kink." The condition for maximum resonance is that—

$$2\pi n L = \frac{1}{2\pi n K},$$

and therefore—

$$n = \frac{1}{2\pi\sqrt{LK}}.$$

Hence L being approximately constant, an increase of n means a decrease of K, *i.e.*, a greater distance apart of the electrodes, if maximum resonance is to occur. Now if the "kink" is due to resonance we may justly infer that it would occur under the conditions of maximum resonance, and an increase of freqnency would move it up the voltage-distance curve. As a matter of fact our experiments show that the movement is in the opposite direction. Most experiments on these lines have been conducted with large spheres and with comparatively low voltages, so that the "kink" has not been obtained. It will be further seen that, in all probability, no "kink" will be found with high frequencies. This can be explained on the hypothesis that it takes an appreciable time to establish the brush discharge, and that under these conditions the pressure is not maintained in the same direction for a sufficient length of time.

Again, if the resonance theory is correct, then, since the inductance of the circuit is practically constant, we should expect that the "kink" would always appear when the gap had a given constant capacity. Now the capacity of the gap increases slightly faster than the radius of the spheres (a) increases, and decreases more slowly than the distance (x) between them increases. Thus if (a) and (x) are increased in the same ratio, the increase of capacity due to the increase of (a) is greater than the corresponding decrease due to the increase of (x), and the net result therefore is an increase in the capacity. From our results x/a at the "kink" is fairly constant and therefore an increase in (a) leads to a proportionate increase in (x), and from the above considerations, it is impossible that the capacities at the various "kinks" should all be equal. Thus the resonance theory does not appear to be tenable. It has been observed by other experimenters that variations in the reactance and resistance of the circuit affect the production of the brush discharge. We have found that similar alterations also affect the position of the "kink." As has been previously pointed out, the "kink" is sometimes absent when there is a very high humidity, and this fact may be explained on the ground that an abnormal amount of water vapour may cause the brush discharge to come on at a lower electric intensity and to appear gradually.

LOCALISATION OF BREAKS IN SUBMARINE CABLES.

By W. H. YOUNG, B.Sc., Student.

(*Abstract of Paper read before the Students' Section at Glasgow, on November* 19, 1909.)

Kinds of Breaks.—Breaks in submarine cables naturally divide themselves into two distinct classes. The most common kind of break is that in which the copper end is exposed to the sea-water, or mud, making a more or less good "earth." The distance away of such a break is got at by resistance measurements. The fracture may, however, occur in such a manner that the easily stretched insulator is drawn over the end of the copper, insulating it more or less thoroughly, and producing what is called a "sealed" end in distinction to the "open" end of the first class of break. Sealed ends are located by measurements of capacity.

The first part of this paper will deal with "open" ends, which are located by resistance measuring tests, generally with the Wheatstone bridge. The greatest part of the science and practice of cable repair consists of expert Wheatstone bridge manipulation.

Sullivan Galvanometer.—The galvanometer used in conjunction with the bridge in most cable companies' services is Sullivan's Marine galvanometer, of which a detailed description will be found in Munro and Jamieson's "Pocket Book of Electrical Rules and Tables."

Battery.—The batteries used are usually formed of agglomerate Leclanché, dry cells, or some similar not too expensive cell, of low internal resistance, steady E.M.F., and slight polarisation. A battery of 100 cells, arranged so that the number in use can be varied at will, is fairly usual.

The procedure of measuring the resistance of a cable with its far end broken in sea-water differs from taking an ordinary Wheatstone bridge measurement, because the following points have to be considered in the former case.

The resistance consists of two parts: one the resistance up to the break—which is what is wanted, and the other the resistance of the end to earth. What is measured is the sum of these, and to make the result useful, the two parts must be separated.

The resistance of the cable up to the break is that of a length of copper wire, it therefore obeys Ohm's law in every respect.

The resistance of the end to earth does not obey Ohm's law, being different with different strengths of current flowing through the exposed area of copper. It is also different with + and — currents.

Earth Currents.—Earth currents are in most cases fairly constant over short periods, but over longer periods they change considerably in strength, and even reverse. Occasionally a case occurs where the earth current changes violently and continuously.

Fault Current.—The end of a broken cable in sea-water acts as a small battery, the copper conductor forming one pole, the iron armour wires the second, and the sea-water the electrolyte. This will cause a feeble current, which blends with the earth current.

Electrolytic Action of Cable End.—When the testing battery is applied, an electrolytic action is set up at the exposed end owing to the passage of current from the copper through sea-water to the iron sheathing wires and earth. When the positive pole of the battery is applied at one end, a coating of cuprous chloride is deposited on the exposed copper, while hydrogen gas is given off at the iron wires; but when the negative pole is applied the hydrogen is given off from the copper, and an iron salt forms on the sheathing. Naturally the presence of these deposits and hydrogen have a considerable effect on the resistance of the exposed end, and the phenomena must therefore be carefully considered by cable electricians. Moreover, these deposits on the electrodes which the end thus forms cause them to act like the poles of a secondary battery, and to urge a current in the opposite direction to that of the testing battery. This secondary current appears and disappears from the circuit along with the cuprous chloride and hydrogen which give rise to it, and this fugitive current is one of the worst difficulties to contend with in many cable tests. These phenomena are generally called "polarisation" in works on this subject.

The cuprous chloride deposited on the conductor is soluble in water, but it may remain on the wire for a short time after it is formed. Its disappearance can be hastened by applying the negative current to line, when the hydrogen bubbles generated thereby quickly break up the film of the salt.

The effect of the deposit of cuprous chloride is considerably to increase the resistance of the end; hence, generally a higher resistance is obtained with the positive pole of the battery to line than with the negative. This, however, is not invariably the case, as sometimes—say when the end is deep in thick mud and the hydrogen bubbles cannot readily escape—the resistance may be more with the negative current.

Kennelly's Law.—The resistance offered by an end in sea-water depends also on the strength of current traversing a given exposed area, being less with a large current density than with a small one. This variation follows, with negative testing currents, a definite law, experimentally established by Professor Kennelly, viz., that with a constant area

of exposure in sea-water the resistance of the end varies inversely as the square root of the traversing current.

Gathering together our facts, it is seen that the resistance of an end depends on—

(*a*) The area exposed.
(*b*) The strength and direction of the current traversing that area.
(*c*) The polarisation of the end.

False Zero Experiment.—One cannot very well learn to take accurate tests to false zero merely by reading about it. Some idea of the phenomena may be derived by the following simple experiment :—

Connect up a Wheatstone bridge in the usual way (Fig. 1), employing a battery of variable E.M.F., or if that is not available the E.M.F. can

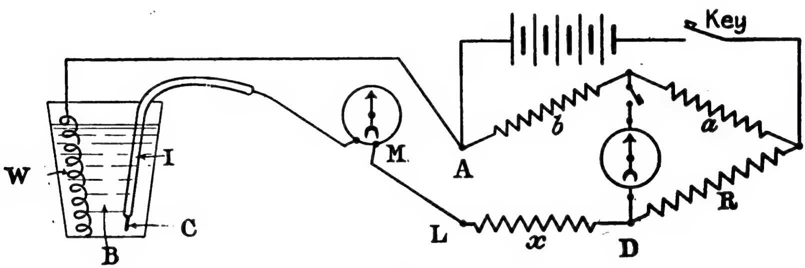

FIG. 1.

M Milliampere meter.
W Wire coil (bare).
I Insulated wire with exposed copper (C) at end.
B Bucket containing salt water.
X Coil resistance.

be varied by means of an adjustable resistance in the battery circuit. For the unknown resistance x any coil of, say, from 100 to 1,000 ohms may be used, and to one end L of it attach a piece of rubber or gutta percha insulated wire, the other end of which dips in a bucket of salt-water. From the point A of the bridge run a lead to a coil of galvanised iron wire immersed in the water, but not touching the wire L C. With this simple apparatus a fair idea of measuring to false zero can be derived. It will be found that x', the resistance obtained, will always exceed x, the true resistance of the coil L D, and that $x' - x$ can be varied by altering the E.M.F. of the battery, by reversing the battery, or by altering the area of copper exposed at C. If this area is small, it will be found possible to run it up to a fairly high resistance by prolonged application of a positive testing current. If a milliammeter be placed in the circuit L C the curves may be drawn for different areas of copper exposed at C, of $x' - x$ or x, the end resistance, and I, the current through the end. By plotting x and $\frac{1}{\sqrt{I}}$ the truth of Kennelly's law may be

tested. This experiment differs from practical work owing to the absence of the capacity of cables and its disturbing effects. There is also no earth current, but fault current and polarisation may be studied.

Capacity Effect on False Zero.—When a piece of cable is connected up to the bridge with the galvanometer key closed, and the battery is switched on, the potential at L rises faster than that at C owing to the capacity of the cable in the arm L C, which causes a throw on the galvo scale. Instead of stopping at false zero at the end of the return movement of the throw, the spot still continues sliding or creeping more or less rapidly across the scale owing to the polarisation of the end, and the difficulty is to estimate where the movement due to capacity ends and that due to polarisation begins, that point being the correct false zero. When a long length of cable is in circuit the capacity is too large to keep the galvanometer key down when switching the battery off or on, and it is necessary to open the galvanometer key for perhaps several seconds to protect the delicate suspension from the violent swing caused by the first rush of current.

This introduces what is called a "false zero interval," and still further complicates matters, because during those seconds that the galvanometer was cut out the polarisation of the end was going on, and consequently the false zero changing, so that the result obtained on balancing after switching in the galvanometer is higher than the actual minimum resistance. Fortunately in this case the resistance of the long cable makes the polarisation current small, and therefore helps to reduce the error.

Taking a False Zero Test.—Let us now suppose we have a cable connected up to a Wheatstone bridge, with battery and necessary keys in circuit. First depress the galvanometer key; the spot will move from the instrument zero and take up a position at false zero, more or less steady. Note that position. Now release the galvanometer key, press down the battery key, then after a second or so, depending on the capacity of the cable, press down the galvanometer key again and rapidly balance the bridge to false zero. As soon as the reading is obtained open the galvanometer key first, and then switch off the battery. False zero should again be taken, it will probably be different this time, and another balance taken to this new false zero. If taken quickly and skilfully the mean of two such readings should give a very close approximation to the resistance up to and including the end. Needless to say, the operator's skill and quickness in handling the Wheatstone bridge have a great influence on the accuracy of his results.

Kennelly's Test to False Zero.—Kennelly's law, that the resistance of an end exposed in sea-water varies inversely as the square root of the current density through the exposed area, has been already mentioned. From it a test may be derived which gives us the resistance of the conductor up to the break, thus eliminating the end resistance.

For this, two tests to false zero are taken with two different current strengths—C_1 and C_2. Let R_1 and R_2 be the readings obtained. Each

of these results R_1 and R_2 include the resistance up to the end, say x, the same in both cases, and the end resistance which will be, say f_1 and f_2, in the two cases.

Then—

$$R_1 = x + f_1$$
$$R_2 = x + f_2,$$

transposing—

$$\frac{f_1}{f_2} = \frac{R_1 - x}{R_2 - x}.$$

By Kennelly's law—

$$\frac{f_1}{f_2} = \frac{\sqrt{C_2}}{\sqrt{C_1}},$$

hence—

$$x = \frac{R_1\sqrt{C_1} - R_2\sqrt{C_2}}{\sqrt{C_1} - \sqrt{C_2}}.$$

In practice this formula is generally put into the more useful shape—

$$x = R_1 - d\frac{\sqrt{n}}{\sqrt{n} - 1}$$

where—

$$n = \frac{C_1}{C_2}, \text{ the ratio of currents,}$$

and—

$$d = R_1 - R_2.$$

Tables of $\frac{\sqrt{n}}{\sqrt{n}-1}$ are calculated for different values of n, and kept handy when tests are being made. This test is made with negative current to line. The currents through the break should lie between 5 and 25 milliamperes, and they are most easily determined by introducing a milliammeter between the bridge and the cable. With higher or lower currents through the break the results are often less reliable, it is said, owing to restriction of free generation of hydrogen gas with currents of very low or high magnitude.

Kennelly's test, though far from infallible, will often, if taken carefully, give a very close approximation to the distance of the break, and, used in conjunction with other tests, it generally gives useful information as to the probable resistance to be deducted for the end.

Notes on Equipment, etc.—The various instruments, switches, commutators, multiple-way plug-pieces, etc., necessary for the performance of the electrical tests in everyday use, are mounted on a testing table and permanently connected up with leads. The connections for any particular test ought to be made by inserting or withdrawing a few plugs, or moving switches, and the best arrangement of apparatus is that which enables the electrician to prepare his table for all of his usual tests with the minimum loss of time and number of alterations.

The most usual tests are: Bridge tests (including Kennelly's, Schae-

fer's, etc.), loop tests, capacity tests (Ballistic and Gott's), and insulation tests by direct deflection and comparison. It will also be necessary to change over from testing to sending and receiving telegraphic messages.

The arrangements of the testing table vary on all cable steamers, as the instruments are usually connected up by, or under the supervision of the chief electrician, who will arrange it to suit himself. If enough instruments are available, it is a good plan to have them arranged in two sets, each set occupying about half of the testing table, and including a Sullivan galvanometer, with its shunts and battery, reversing key in battery circuit, short circuit, and reversing key in galvanometer circuit, etc., and to use one side of the table and one set of instruments for all tests requiring a Wheatstone bridge, the other side of the table being reserved for tests not requiring the bridge, such as capacity tests, insulation tests, etc. The lamp-rack and scale can then run along a slide stretching across the centre of the table, so as to be used for the galvanometer in each set. This arrangement of instruments will allow a large variety of tests to be carried out with few and simple alterations of plugs and switches. On the Wheatstone bridge side of the table there will be the bridge, Sullivan galvanometer, and shunt; syphon recorder, Kelvin mirror galvanometer, or other "speaking" instrument; reversing keys in both battery and speaking instrument circuits; an adjustable resistance in the battery circuit for adjusting the testing current, a milliammeter, a small standard condenser, a standard cell, and multiple-way plug-pieces, switches, cable terminals, etc., as necessary.

On the other side of the table there will be the galvanometer and shunt, reversing and short-current keys in galvanometer circuit, reversing key in battery circuit, a set of slide resistances (for use in Gott's and other tests), standard high resistances, standard condensers, and, as before, the necessary plug, switches, etc., to combine the set in the required arrangement.

In the bridge set it will be found useful to have a Kelvin mirror galvanometer, with coil suspended in glycerine so as to make the instrument rather "stiff," to be used in place of the delicate Sullivan galvanometer when dealing with short lengths of cables. It will generally be found that the electrician will have a dozen or more short pieces to test for every time he has to test a long cable, and for such work the sensitiveness of the Sullivan galvanometer is a nuisance. A Kelvin mirror galvanometer of the type mentioned above can easily stand the violent swings caused by the charge or discharge of the cable capacity when a powerful battery is switched on or off, so that the galvanometer key can be clamped down when testing, and readings taken to false zero, without any false zero interval, by manipulating the battery key only. This type of galvanometer is quite sensitive to 1 ohm in 1,000 ohms, and the use of it in the above way will prevent the operator from mistaking a near break with a high resistance end for a distant break with a low resistance end, because the galvanometer being always across the bridge terminals, he will see the capacity kick on switching on or off

his battery, and if the kick is very small in view of the resistance in circuit, he will be warned of a high end resistance. On the contrary, the Sullivan galvanometer gets one into the habit of always keeping the galvanometer circuit open until a second or so after the battery is switched on, and of opening it again before the battery is switched off, so that the charge or discharge throw is not seen and its evidence perhaps not considered. Serious mistakes are on record as having occurred through neglecting this simple precaution. For taking resistances of less than 800 ohms the Sullivan galvanometer appears to the author to be an unnecessary refinement, productive of more harm than good.

For capacity measurements by the ballistic method, on the other hand, the Sullivan galvanometer should always be used. The Kelvin instrument is anything but satisfactory for this test.

In all the tests considered in this paper it has been assumed that there is only one break or fault to be located. In practice it often happens that one or more faults intervene between the testing end and a break or another fault, and the task of locating the latter then becomes more complicated and uncertain. Sometimes the presence of such intervening faults is known, sometimes it is not, especially in cable

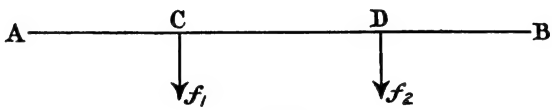

FIG. 2.

systems in which regular routine testing of all sections does not take place. The mere knowledge of the presence of an intervening fault is not enough, except to make the electrician more cautious even than usual. A knowledge of its position and resistance is essential if it is to be properly allowed for in the location. Its resistance is not a constant. Let us consider a simple case, a cable with two faults in it, f_1 and f_2 (Fig. 2).

If tests from both A and B are available, or if there is a sound loop cable between A and B, the discrepancies between A and B's tests will be enough to indicate to the testers that there are two faults. If there is only one electrician and no loop cable, the interference of two varying fault resistances will generally cause such inconsistencies in the results of Blavier tests from one end that an experienced man will soon see how the land lies. In a case like this, the Blavier test is more likely to give correct results than either the loop or the earth overlap tests, though the latter are vastly superior when there is only one fault. A little consideration will show that the presence of the second fault rather tends to correct the chief natural inaccuracy of the ordinary Blavier test, by making the currents which traverse f, while end B is freed and earthed, more nearly the same. In a case like this it is the best policy to locate the worst fault from the

side nearest to it, as near as possible by the Blavier test, and make sure of lifting the cable a little to the far side of this fault, so as to get in between them, when it will be a simple case of locating a single fault each way. If both faults are of too high resistance to be correctly obtained by the Blavier test, it may be a good plan to "cut in" at any convenient place in the cable between C and D, take tests both ways, splice up again if the cut-in is not near either fault, and then proceed to remove the faults, which can be easily located from any point between them.

ORIGINAL COMMUNICATION.

THE THEORY OF THE STATIC BALANCER.

By C. C. HAWKINS, Member.

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Although the general principle of the static balancer used in connection with a single dynamo feeding a 3-wire network is simple and well understood, there are certain less-known details in its actual working which deserve attention in a scientific statement of its theory, and which have some practical bearing as showing in what direction the commonly accepted version is only approximately true. The use of the apparatus or its equivalent—viz., the connection of the third wire to the star-point of the secondaries of transformers feeding a rotary converter—has become more extended of recent years; yet so far as the writer is aware, since the articles published by Professor A. Sengel,* but little theoretical consideration has been paid to the system by English writers. The present rigorous examination of the system in detail is intended to show what are the terms that are usually neglected, and how far this is legitimate. It finally leads to a simple practical formula for determining the value of the out-of-balance current for the use of the designer.

The theory of the static balancer is usually treated on the basis of a superposition of three systems of current: (1) A direct current C_b of equal value in each side of the network and therefore flowing in series through it; (2) an alternating current i flowing in series—*e.g.*, through the two limbs of a single-phase or, as it is more correctly regarded, 2-phase balancer; and (3) an out-of-balance system giving as its final result the difference C_0 between the actual currents C_2 and C_1 in the two sides of the network.

Taking the simple 2-phase case, the system of Fig. 1 may be reduced to the skeleton form of Fig. 2, which also gives the several resistances and induced E.M.F.'s. Each limb of the balancer has a resistance of ρ ohms, and except when the tappings to the slip-rings pass the brushes, the balancer divides each half of the armature into two portions, fb, bd, which are fractions q and $(1-q)$ of the length between f and d. If R_a = the joint resistance of all paths of the armature from + to

* *Elektrotechnische Zeitschrift*, May 17 and 24, 1900.

— brushes, one-half of the armature which may itself consist of several parallel paths will have a resistance of $2 R_a$ ohms, and the resistances of the portions fb and $b d$ will be respectively $2 R_a q$ and $2 R_a (1 - q)$. As rotation proceeds, q increases from 0 to 1.

When it is desired to construct equations that hold *simultaneously* for the three systems, it is evident that the iron of the armature and

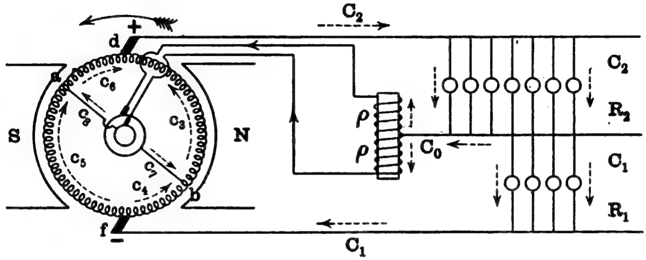

FIG. 1.—Two-phase Balancer Connections.

pole-pieces must be taken as having reached its final resultant state. Let E_3, E_4, E_5, and E_6 be the instantaneous E.M.F.'s induced in the four portions of the armature winding; under load the inducing field is distorted forward by the armature reaction, and the equality of the E.M.F.'s E_3 and E_6 or E_4 and E_5—*i.e.*, zero impressed E.M.F. on the

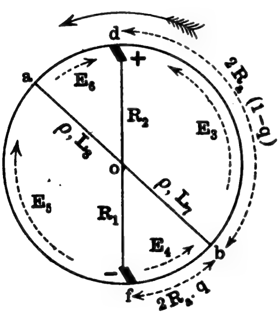

FIG. 2.—Diagrammatic Form.

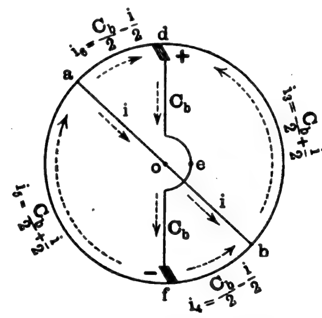

FIG. 3.—C_b and i System with Third Wire Disconnected.

balancer—always occurs *after* $q = \frac{1}{2}$. Let L_3, L_4, L_5, and L_6 be the *instantaneous* (not necessarily constant) final inductances of the four portions of the armature winding, and L_7 and L_8 those of the two limbs of the balancer (supposed for the present to be wound on separate cores). Then on a balanced load, or on any load so long as the external network is disconnected from the centre of the balancer, $E_3 = E_5$, $E_4 = E_6$, $L_3 = L_5$, and $L_4 = L_6$. But more than this, *in a drum armature*, even if, as will be found to be the case, the final current c_3 differs

from c_5 in the opposite section, and c_4 differs from c_6, yet since the armature windings pass under, and are affected by corresponding portions of poles of opposite sign, the iron will be under the influence of both c_3 and c_5, or of both c_4 and c_6, and the instantaneous L_3 will $= L_5$, and $L_4 = L_6$. Therefore, under all circumstances in the drum armature—

$$E_3 = E_5 \qquad L_3 = L_5$$
$$E_4 = E_6 \qquad L_4 = L_6$$

although the rates of change of c_3 and c_5 may still remain different, or, again, $\frac{d\,c_4}{d\,t}$ and $\frac{d\,c_6}{d\,t}$ may differ from one another.

In the first place, let the middle of the network—*i.e.*, the third wire—be entirely disconnected from the centre of the balancer, as shown in Fig. 3. Then the joint system of C_b and i is symmetrical in the further sense that the currents due thereto in each of the portions of the armature of uneven suffix remain at every instant equal, and those of even suffix are equal. That is, if i_3, i_4, etc., are the resulting currents from C_b and i (no out-of-balance currents being as yet possible), the condition of Fig. 3 is reached, in which the armature currents are divisible into two *similar pairs*, viz. :—

$$i_3 = i_5 = \frac{C_b}{2} + \frac{i}{2}$$
$$i_4 = i_6 = \frac{C_b}{2} - \frac{i}{2}$$

just as in a single-phase rotary converter.

The true instantaneous currents are then :—

Direct—

$$C_b = \frac{E_a - i\,R_a\,(1 - 2\,q) - \left(L_3 \frac{d\,i_3}{d\,t} - L_4 \frac{d\,i_4}{d\,t}\right)}{R_1 + R_2 + R_a} \quad . \quad . \quad . \quad . \quad (1)$$

Alternating—

$$i = \frac{E_3 - E_6 - C_b\,R_a\,(1 - 2\,q) - \left(L_3 \frac{d\,i_3}{d\,t} + L_4 \frac{d\,i_4}{d\,t}\right) - (L_7 + L_8)\frac{d\,i}{d\,t}}{2\,\rho + R_a} \qquad (2)$$

It is evident that the alternating current reacts through the ohmic resistance of the armature upon the C_b system, and causes its value and the terminal voltage for an assumed constant armature E.M.F. to pulsate slightly. The two systems depend upon each other, so that when the balancer circuit is closed across the armature the instantaneous value of the new direct current C_b is, except at particular moments, different from the initial value $C = \frac{E_a}{R_1 + R_2 + R_a}$. Here R_1 and R_2 are the effective resistances on the positive and negative sides of the network respectively, whether from lamps or motors (the shunt current and resistance of any series winding being at present, for the sake of simplicity, neglected).

Since C_b itself pulsates, the rates of change of i_3 and i_4 are not the same numerically, and are not each equal to half the rate of change of i in the balancer; hence the necessity for introducing the full terms $L_3 \frac{d\,i_3}{d\,t} \mp L_4 \frac{d\,i_4}{d\,t}$ instead of simply $\frac{1}{2}(L_3 \mp L_4)\frac{d\,i}{d\,t}$.

Since C_b and i are mutually interdependent, one or other must be independently determined by Kirchhoff's laws (see Appendix).

Let j_b = the instantaneous divergence of the potential of the (unconnected) third wire from its correct value midway between the potentials of the brushes. When R_1 is $> R_2$, or the *positive* side of the network has the lower resistance and is the more heavily loaded, j_b is *positive* or above the true mean. Then—

$$j_b = (R_1 - R_2)\frac{C_b}{2} = \frac{R_1 - R_2}{R_1 + R_2}\cdot\frac{v_{eb}}{2} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where v_{eb} is the instantaneous value of the pulsating brush voltage. Evidently j_b must be half the difference in the volts expended respectively over the two sides of the network in the passage of C_b.

As compared with the original divergence without any balancer, viz. :—

$$J_0 = (R_1 - R_2)\frac{C}{2} = \frac{R_1 - R_2}{R_1 + R_2}\cdot\frac{V_e}{2} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

j_b for an assumed constant induced E.M.F. E_a will in general differ from J_0, and only becomes identical with it at the particular moment when C_b becomes identical with C, *i.e.*, when $q = \frac{1}{2}$, and $L_3 = L_4$.

By the junction of the third wire to the centre of the balancer it is now desired to reduce the divergence from J_0 or j_b to some lower value j_c, as nearly zero as the resistance of the balancer and armature permits.

In order to trace the effect of the centre connection, the first step must be to determine the difference of potential between the third wire and the centre of the balancer before connection is made. Under the joint system of C_b and i, from the symmetry of their arrangement, the mean of the brush potentials is always equal to the mean of the potentials at the two ends of the balancer. *I.e.*, if a, b, d, and f are the actual potentials in Fig. 3—

$$\frac{d + f}{2} = \frac{a + b}{2}.$$

But the centre point of the balancer will not be at this mean value unless $L_7 = L_8$. When they are different the potential of the centre point diverges from the instantaneous mean $\frac{a + b}{2}$ by the instantaneous amount—

$$\frac{L_7 - L_8}{2}\cdot\frac{d\,i}{d\,t}.$$

Now j_b is the divergence of the third-wire potential from $\frac{d+f}{2}$. The total instantaneous difference of potential between the third wire and the centre of the balancer is therefore—

$$e = j_b - \frac{L_7 - L_8}{2} \cdot \frac{d\,i}{d\,t} = j_b + \frac{L_8 - L_7}{2} \cdot \frac{d\,i}{d\,t} \quad . \quad . \quad . \quad . \quad (5)$$

Or suppose the centre of the balancer to be earthed, then the numerical value of the potential of the positive brushes would differ from the numerical value of the potential of the negative brushes by the amount $(L_8 - L_7)\frac{d\,i}{d\,t}$, and the absolute value of the potential of the third wire before connection would be e.

The true method of superposing the out-of-balance components is then at once apparent. The result of connecting the third wire at

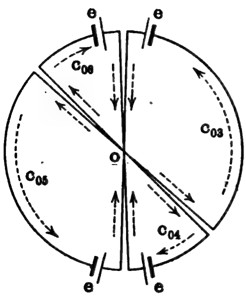

FIG. 4.—System of Out-of-balance Components.

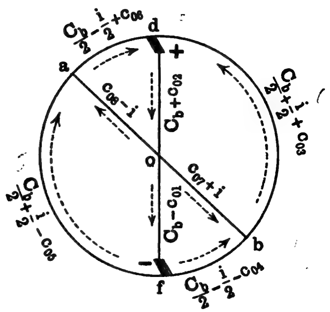

FIG. 5.—Complete System.

potential e to the centre assumed as at zero potential must be to call into existence a system of out-of-balance components which in the 2-phase case will in *each* of the four portions of the system exactly consume the voltage e. Each equalising current flows round one of the four circuits *from* the point of low potential *to* the point of high potential, and by its passage calls for a voltage exactly equal to e. Let c_{03}, c_{04}, c_{05}, c_{06} be the out-of-balance components in the four portions of the armature winding, the suffix o indicating "out-of-balance"; each may in imagination be regarded as completed by its proportionate shares of a balancer limb and of a side of the network to form four separate circuits (Fig. 4).

It may here at once be premised that the value of each of the out-of-balance components varies continuously as rotation proceeds and q increases from o to 1. In each section, therefore, account has to be taken of the self-induced E.M.F.'s due to the rates of change $\frac{d\,c_{03}}{d\,t}$, $\frac{d\,c_{04}}{d\,t}$, etc., which will also go either to help or check the equalisation of e.

As shown in Fig. 4, the necessary out-of-balance components are alternately clockwise and anti-clockwise.

The E.M.F.'s represented by cells in Figs. 4 and 6 might equally well be located in the sides of the network R_1 and R_2, but this does not so clearly indicate that the driving E.M.F. of the out-of-balance system in one section comes out of the induced armature E.M.F., and in the adjacent section on the same side of the network is, as it were, saved. This does not, however, imply that the resultant *terminal* E.M.F. is unaffected; the amperes are increased and the terminal voltage as compared with that corresponding to C_b is lowered,* although the total output for constant E_a is increased. What is meant is that the superposition of system (3) only affects the joint system of (1) and (2) by virtue of alteration of the iron inductances, so that if the final iron inductances are assumed at the outset in the expressions for C_b and i, then these expressions still continue to hold good, and are unaffected by the out-of-balance system.

The extension to the case of any even number n of phases is simple. The limbs of the balancer on one side of the network diameter fd

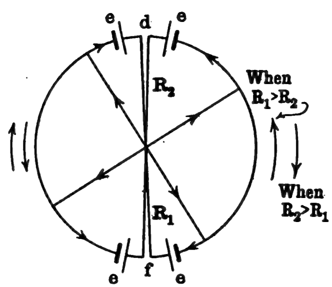

FIG. 6.—Four-phase Balancer.

(Fig. 6) are, as it were, so many parallel paths linked up by a portion of the armature of resistance $\frac{4 R_a}{n}$ between each pair of limbs. The only difference is that whereas in the 2-phase case the out-of-balance current along one limb as $o\,b$ *must* divide in opposite directions at b, in the 4- or 6-phase case it may all continue onwards in the armature in one direction. But wherever in the armature the division in opposite directions does take place, then above this point towards d the amount e is, say, expended out of the armature induced E.M.F., and below this point the same amount e is saved. The 3-phase case is as simple in principle,

* The further reduction in the terminal volts is by the amount—

$$jc\,R_a \cdot \frac{R_1 - R_2}{W},$$

when the E.M.F.'s self-induced by the out-of-balance components are neglected. The value of W is given in the Appendix.

but the actual expressions required become a little more complicated owing to the uneven number of phases.

Returning to the 2-phase case, the out-of-balance component in each section of the armature is in the opposite direction to that of its adjacent neighbour (Fig. 4), but they are additive in each limb of the balancer and in each side of the network. The total out-of-balance current is therefore numerically—

$$C_0 = c_{01} + c_{02} = c_{03} + c_{04} + c_{05} + c_{06}.$$

The complete solution of C_0 is given in the Appendix, and if the E.M.F.'s self-induced by the out-of-balance components be neglected, as there explained, it reduces to—

$$C_0 = e . \frac{2\,W}{U} \quad \dots\dots\dots\dots \quad (6)$$

In the particular case when $q = \frac{1}{2}$, this becomes—

$$C_0 = e . \frac{2\,W'}{U'}$$

where—

$$W' = R_1 + R_2 + R_a$$
$$U' = 2\,R_1\,R_2 + \rho\,(R_1 + R_2 + R_a) + R_a\,(R_1 + R_2 + \tfrac{1}{2}\,R_a).$$

The justification for selecting the particular instant when $q = \frac{1}{2}$ for especial consideration is given later.

If the instantaneous value of L_7 be assumed equal to that of L_8,

$$C_0 = (R_1 - R_2) . C_b . \frac{W'}{U'} \quad \dots\dots\dots \quad (7)$$

But whether the inductive effects of the out-of-balance components are included or neglected, the two portions c_{01} and c_{02} on the two sides of the network are never equal; thus when they are determined only by the ohmic resistances and in the simplest case when $q = \frac{1}{2}$, the division of C_0 is as follows:—

In R_1—

$$\frac{C_0}{2} . \frac{2\,R_2 + R_a}{R_1 + R_2 + R_a},$$

in R_2—

$$\frac{C_0}{2} . \frac{2\,R_1 + R_a}{R_1 + R_2 + R_a}.$$

Their directions are the same relatively to the centre, so that in the one outer the superposed current is opposed to C_b and reduces its value, while in the other outer the two are additive.

The out-of-balance currents in the two limbs of the balancer are also *always dissimilar* except at one moment. Their directions are the same relatively to the centre—*i.e.*, both outwards or both inwards—and in Fig. 4 they are outwards because the positive side of the network

has been assumed to have the lesser resistance and therefore to be the more heavily loaded. Had the negative side been the more heavily loaded, they would have been directed inwards, and the out-of-balance currents in the external network would conversely have been outwards.

Lastly, when the radial currents pass into the armature winding they do not divide equally, nor in inverse proportion to q and $(1-q)$. They are so proportioned that, if e is gained from the induced E.M.F. in one quadrant, it is spent in the neighbouring quadrant on the same side of the armature. It thus results (Fig. 5) that the final currents in the armature, viz.:—

$$c_3 = \frac{C_b}{2} + \frac{i}{2} + c_{03}, \qquad c_4 = \frac{C_b}{2} - \frac{i}{2} - c_{04},$$

$$c_5 = \frac{C_b}{2} + \frac{i}{2} - c_{05}, \qquad c_6 = \frac{C_b}{2} - \frac{i}{2} + c_{06},$$

are in general *always all dissimilar*, and so also those in the balancer, viz., $c_7 = (c_{03} + c_{04}) + i$ and $c_8 = (c_{05} + c_{06}) - i$. In this respect therefore, owing to the unbalanced load, the case of the static balancer is different from the rotary converter.

When the two phases are wound on entirely separate cores, the true alternating current flows onwards through the two coils in series, with the same instantaneous value in each limb and with the same rate of change, yielding a total self-induced E.M.F. $(L_7 + L_8)\frac{di}{dt}$. But the rates of change $\frac{dc_{07}}{dt}$ and $\frac{dc_{08}}{dt}$ are different, and the E.M.F.'s self-induced thereby through L_7 and L_8, even if $L_7 = L_8$, are expended in the several local circuits in modifying the distribution of the out-of-balance components. In this is to be found the solution of the problem of the dissimilar half-waves of current produced by the strong magnetic "bias" of the iron in separate choking coils, as in the case of three transformers feeding a rotary converter with the middle wire of the direct-current network connected to the centre. The true alternating current flows through the three limbs in their proper proportions according to their positions relatively to the armature, but the local out-of-balance currents are distorted out of their normal changing division.

It remains to calculate the new value of the divergence, and at this stage it is necessary to define a counter-clockwise E.M.F. or current round any part of the armature as positive, and in the limbs of the balancer a current outwards from the centre as positive. Thus in limbs 7 and 8 i is respectively positive and negative when it flows from a to b, while c_{07} and c_{08} have the same sign, being both either outwards or inwards. The rate of change of c_7 and c_8 is then positive, if they are outwards and increasing in amount.

From an assumed zero potential at the centre, and proceeding

along the path $o\,b\,d$, we arrive at the potential of brush d as positive and above zero by the amount—

$$d = -(c_{o7} + i)\,\rho - L_7 \frac{d\,c_7}{d\,t} + E_3 - L_3 \frac{d\,i_3}{d\,t} - L_3 \frac{d\,c_{o3}}{d\,t}$$
$$- \left(\frac{C_b}{2} + \frac{i}{2} + c_{o3}\right) 2\,R_a\,(1 - q).$$

Proceeding along the path $o\,a\,f$ we arrive at the potential of brush f as negative and below zero, its value being—

$$f = -(c_{o8} - i)\,\rho - L_8 \frac{d\,c_8}{d\,t} - E_3 + L_3 \frac{d\,i_3}{d\,t} - L_3 \frac{d\,c_{o5}}{d\,t}$$
$$+ \left(\frac{C_b}{2} + \frac{i}{2} - c_{o5}\right) 2\,R_a\,(1 - q).$$

Adding the two together, their sum—

$$d + f = -(c_{o7} + c_{o8})\,\rho - L_7 \frac{d\,c_7}{d\,t} - L_8 \frac{d\,c_8}{d\,t} - L_3 \left(\frac{d\,c_{o3}}{d\,t} + \frac{d\,c_{o5}}{d\,t}\right)$$
$$- (c_{o3} + c_{o5})\, 2\,R_a\,(1 - q),$$

which is the arithmetical difference of the two new brush potentials.

If now half of this sum, but with reversed sign, is added to the potential of the centre, the potential of each brush is altered equally, and they become of equal numerical value but of opposite sign. The divergence of the centre wire from the mean of the brush potentials that is to be found is then equal to the new potential which has been given to the centre, *i.e.*, it is—

$$j_c = C_o \cdot \frac{}{2} + \frac{1}{2} L_7 \cdot \frac{d\,c_7}{d\,t} + \frac{1}{2} L_8 \cdot \frac{d\,c_8}{d\,t} + \frac{1}{2} L_3 \left(\frac{d\,c_{o3}}{d\,t} + \frac{d\,c_{o5}}{d\,t}\right)$$
$$+ (c_{o3} + c_{o5})\, R_a\,(1 - q).$$

Now it can be shown that—

$$(c_{o3} + c_{o5}) = q\,C_o - \frac{1}{2} \left\{ L_3 \left(\frac{d\,c_{o3}}{d\,t} + \frac{d\,c_{o5}}{d\,t}\right) - L_4 \left(\frac{d\,c_{o4}}{d\,t} + \frac{d\,c_{o6}}{d\,t}\right) \right\} \times \frac{1}{R_a}.$$

Therefore without any approximation the final instantaneous value of the divergence after connection of the third wire is—

$$i_c = C_o \left(\frac{\rho}{2} + R_a(q - q^2)\right) + \frac{1}{2}\left(L_7 \frac{d\,c_7}{d\,t} + L_8 \frac{d\,c_8}{d\,t}\right)$$
$$+ \frac{1}{2} L_3 \left(\frac{d\,c_{o3}}{d\,t} + \frac{d\,c_{o5}}{d\,t}\right) q + \frac{1}{2} L_4 \left(\frac{d\,c_{o4}}{d\,t} + \frac{d\,c_{o6}}{d\,t}\right)(1 - q) \quad . \quad (8)$$

The signs of $\frac{d\,c_{04}}{d\,t}$ and $\frac{d\,c_{06}}{d\,t}$ being the reverse of those of $\frac{d\,c_{03}}{d\,t}$ and $\frac{d\,c_{05}}{d\,t}$, the two last expressions act oppositely, and since L_3 is more or less proportional to $(1-q)\,L_a$ and L_4 to $q\,L_a$, where L_a is the inductance of one-half of the armature, their net effect at any time is very small and may be neglected.

The second term may be resolved into—

$$\frac{1}{2}(L_7 - L_8)\frac{d\,i}{d\,t} + \frac{1}{2}\left(L_7\frac{d\,c_{07}}{d\,t} + L_8\frac{d\,c_{08}}{d\,t}\right) \quad . \quad . \quad . \quad . \quad (9)$$

in which the signs of $\frac{d\,c_{07}}{d\,t}$ and $\frac{d\,c_{08}}{d\,t}$ may be the same, so that the mean of their instantaneous rates of change then increases or decreases j_c.

In the more usual case when the two phases or pairs of phases are wound on the same core, let $L_7 = l_7 + M$ and $L_8 = l_8 + M$, where M is the flux due to unit current in one coil which also passes through the second coil, and l_7 and l_8 are the respective leakage fluxes per unit current. Instead of $L_7\frac{d\,c_{07}}{d\,t}$, we then have—

$$l_7 \cdot \frac{d\,c_{07}}{d\,t} + M\left(\frac{d\,c_{07}}{d\,t} - \frac{d\,c_{08}}{d\,t}\right),$$

and instead of $L_8\frac{d\,c_{08}}{d\,t}$ we have—

$$l_8 \cdot \frac{d\,c_{08}}{d\,t} - M\left(\frac{d\,c_{07}}{d\,t} - \frac{d\,c_{08}}{d\,t}\right).$$

From the fact that the instantaneous out-of-balance currents c_{07} and c_{08} are not equal, it is evident that the magnetic effects of the direct-current components can never be strictly balanced, even though the windings may be on the same core. Their rates of change are also different. To take strict account of the mutual inductance of the phases, it is only, however, necessary to write l_7 for L_7 and l_8 for L_8 in the expressions (5), (8), and (9).

Finally, therefore, when the expression (9) is neglected we have simply in the 2-phase balancer—

$$j_c = C_0\left(\frac{\rho}{2} + R_a\,(q - q^2)\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

It has above been shown that even if the system is regarded as non-inductive to the out-of-balance components, the assumption that the current in each limb of the balancer $= \frac{C_0}{2}$ is only approximately true and the division in the armature is in reality not a simple matter. Yet

it is interesting to observe that the above final value for j_c is exactly the same in effect as if C_0 divided equally between the two phases with a loss of $C_0 \cdot \frac{\rho}{2}$ volts in each, and then divided at the junctions with the armature winding into portions $\frac{C_0}{2}(1-q)$ over the resistance $2 R_a q$ and $\frac{C_0}{2} \cdot q$ over the resistance $2 R_a (1-q)$, requiring in either case an additional voltage $= C_0 R_a (q - q^2)$.

The average value of $q - q^2$ between $q = 0$ and $q = 1$ is $1/6$, and due to the peculiarity noted above this correct result has often been arrived at, and is well known. Yet the actual distribution of currents which has been made the starting-point of the proof has usually been erroneously stated.

The average value of the armature resistance term has been extended by Professor A. Sengel to the case of n-phases in the generalised expression $R_a\left(\frac{1}{12}+\frac{1}{3n^2}\right)$, but it is obvious that to obtain the true average value of j_c the whole expression including C_0 should in strictness be averaged, since C_0 itself pulsates.

The pulsation of both j_c and C_0 was noted by Professor Sengel, who showed that hot-wire instruments indicating the R.M.S. value gave higher readings than polarised instruments. In his experiments the *average* value of C_0 was *measured,* and in combination with the average armature resistance term was found to give values of j_c, agreeing moderately well with the measured values. But for the purpose of design it does not appear that any virtue can be claimed for the average value of the armature resistance in the absence of knowledge of the average C_0. When practical values are given to the various quantities, it will be found that the changing numerator and denominator of C_0 are dominated by the rise and fall in the value of U on either side of $q = \frac{1}{2}$, so that on the whole C_0 is at its maximum when $q = 0$ and at its minimum when $q = \frac{1}{2}$.

In consequence j_c remains more nearly constant, and when, as in practice, R_a is about 5 per cent. of $R_1 + R_2$ under approximately full load, the whole range of fluctuation is so small that it is quite as accurate to take the simplest case of $q = \frac{1}{2}$, when the alternating current has no effect on C_b. At this moment, neglecting any E.M.F.'s self-induced by the out-of-balance components, we also have in general for any number of phases—

$$j_c = \frac{C_0}{n}\left(\rho + \frac{R_a}{2}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

It then becomes possible to state from the designer's point of view the necessary data which determine the value of C_0 in terms of the assumed constant E_a and of the resistances. C_b becomes identical with the initial current C, or more accurately with allowance for the

shunt current c_s and shunt resistance R_s in parallel with the external network—

$$C_a = \frac{E_a}{\frac{(R_1 + R_2) R_s}{R_1 + R_2 + R_s} +} \quad \ldots \ldots \quad (12)$$

and—

$$j_b = \frac{R_1 - R_2}{2}(C_a - c_s) \quad \ldots \ldots \quad (13)$$

The desired quantities in the 2-phase case then reduce to—

$$C_0 = \frac{(R_1 - R_2)\left[E_a - c_s\left(\frac{(R_1 + R_2) R_s}{R_1 + R_2 + R_s} + R_a\right)\right]}{2 R_1 R_2 + \rho (R_1 + R_2 + R_a) + R_a (R_1 + R_2 + \frac{1}{2} R_a)} \quad . \quad (14)$$

$$j_c = \frac{C_0}{2}(\rho + \tfrac{1}{2} R_a),$$

and in the 4-phase case—

$$C_0 = \frac{(R_1 - R_2)\left[E_a - c_s\left(\frac{(R_1 + R_2) R_s}{R_1 + R_2 + R_s} + R_a\right)\right]}{2 R_1 R_2 + \frac{\rho}{2}(R_1 + R_2 + R_a) + \frac{1}{2} R_a \left(R_1 + R_2 + \frac{R_a}{4}\right)} \quad . \quad (15)$$

$$j_c = \frac{C_0}{4}(\rho + \tfrac{1}{2} R_a).$$

In the 3-phase case the denominator becomes—

$$2 R_1 R_2 + \tfrac{2}{3}\rho (R_1 + R_2 + R_a) + \tfrac{2}{3} R_a (R_1 + R_2 + \tfrac{1}{6} . R_a)$$

and—

$$i_c = \frac{C_0}{3}(\rho + \tfrac{1}{2} R_a) \text{ very nearly.}$$

When there are more than two phases the current through the network and shunt when the third wire is disconnected does not strictly return to (12) even when $q = \frac{1}{2}$. The amount of approximation involved in this assumption and the further approximation in the denominator is indicated in the Appendix; both are so small that the above expressions for the 3- and 4-phase cases are closely true.

In both cases any E.M.F.'s due to the out-of-balance components themselves are neglected, and the inaccuracy in the denominators due to the presence of the shunt circuit is negligible, since so far as the out-of-balance components are concerned, the potentials of the brushes are so nearly the same that little current flows *viâ* the shunt. Since the series coils are preferably divided between the positive and negative outers, their resistance may be taken into account in the values assigned to R_1 and R_2, which must necessarily be known or estimated at the outset.

It needs only, then, to be borne in mind that though C_0 is at its lowest limit, yet owing to the variations of the armature resistance term outweighing C_0's variation, j_c is at its maximum and the worst case has been taken.

APPENDIX.

An E.M.F. or current round any portion of the armature in a counter-clockwise direction being taken as positive, the sign of the current i and of its rate of change $\frac{d\,i}{d\,t}$ can be fixed by reference to the armature, and for this purpose will be chosen the sign or direction of $\frac{i}{2}$ in the arc which has 3 for its suffix. A current flowing upwards in this arc 3 is by the above convention reckoned as positive. Similarly a positive rate of change of C_b is to be interpreted as meaning an increasing value of C_b in an upward direction in the right-hand half of the armature of Fig. 3.

I. The true instantaneous values of C_b and i are then found as follows:—

Let the mean of the E.M.F.'s round the path O $b\,d$ and round the path O $a\,f$, *i.e.*—

$$E_3 - L_3 \cdot \frac{d\,i_3}{d\,t} - \frac{L_7 + L_8}{2} \cdot \frac{d\,i}{d\,t} = S - h,$$

and the mean of the E.M.F.'s round the path O $a\,d$ and round the path O $b\,f$, *i.e.*—

$$E_4 - L_4 \frac{d\,i_4}{d\,t} + \frac{L_7 + L_8}{2} \cdot \frac{d\,i}{d\,t} = T + h.$$

Since—

$$i_3 = \frac{C_b}{2} + \frac{i}{2},$$

and—

$$i_4 = \frac{C_b}{2} - \frac{i}{2},$$

and the rate of change of i far outweighs that of C_b, it follows that the final effect of $-L_4 \frac{d\,i_4}{d\,t}$ is opposite in sign to that of $-L_3 \frac{d\,i_3}{d\,t}$.

Let—

$$\rho\,(R_1 + R_2 + R_a) + \tfrac{1}{2}\,R_a\,(R_1 + R_2) + 2\,R_a^2\,(q - q^2) = W.$$

Then—

$$C_b = \frac{S\,(\rho + R_a \cdot q) + T\,[\rho + R_a\,(1 - q)] + h\,R_a\,(1 - 2\,q)}{W} \quad . \quad (16)$$

$$i = \frac{S\,(R_1 + R_2 + 2\,R_a \cdot q) - T\,[R_1 + R_2 + 2\,R_a\,(1 - q)] - 2\,h\,(R_1 + R_2 + R_a)}{2\,W} \quad (17)$$

II. In order to solve for C_0 in the 2-phase case, let x; y, z, w be the cyclic symbols for the currents in the four circuits, the positive direction of each being counter-clockwise, so that $x = c_{03}$, $y = -c_{04}$, $z = c_{05}$,

and $w = -c_{06}$. The E.M.F. e is oppositely directed in alternate circuits, and appears, therefore, alternately positive and negative. When arranged for solution by determinants the four simultaneous equations are :—

$$+[\rho + 2\,R_a(1-q) + R_2]\,x - \rho\,y - O\,z - R_2 . w$$
$$= \quad e - L_3\frac{d\,x}{d\,t} - L_7\frac{d\,(x-y)}{d\,t}$$

$$-\rho\,x + (\rho + 2\,R_a . q + R_1)\,y - R_1\,z - O\,w$$
$$= -e - L_4\frac{d\,y}{d\,t} + L_7\frac{d\,(x-y)}{d\,t}$$

$$-O\,x - R_1\,y + [\rho + 2\,R_a(1-q) + R_1]\,z - \rho\,w$$
$$= \quad e - L_3\frac{d\,z}{d\,t} - L_8\frac{d\,(z-w)}{d\,t}$$

$$-R_2\,x - O\,y - \rho\,z + (\rho + 2\,R_a . q + R_2)\,w$$
$$= -e - L_4\frac{d\,w}{d\,t} + L_8\frac{d\,(z-w)}{d\,t}$$

All the rates of change, dx/dt, dy/dt, dz/dt, dw/dt, have the same sign throughout the half-cycle from $q = 0$ to $q = 1$, the apparent anomaly of these currents continually increasing or decreasing being explained by the fact that the same counter-clockwise direction is retained as positive in each section. The signs of $\frac{d\,c_{04}}{d\,t}$ and $\frac{d\,c_{05}}{d\,t}$ are the reverse of those of $\frac{d\,y}{d\,t}$ and $\frac{d\,w}{d\,t}$, so that actually when the current in one section is rising it is falling in its neighbour. As the component c_{03} rises, say, from $q = 0$ to $q = 1$, the component c_{06} falls from the same maximum to the same minimum, so that at the end of a half-cycle c_{03} may be said to be continued as c_{06}, and c_{04} as c_{05}. The signs of the rates of change in the balancer limbs being fixed by x and z, they agree with the convention previously adopted for $\frac{d\,c_{07}}{d\,t}$ and $\frac{d\,c_{08}}{d\,t}$.

Let—

$$m_1 = \rho\,(R_1 + R_2 + R_a) + 2\,R_a^2(q - q^2) + R_1\,R_a\,q + R_2\,R_a(1-q).$$
$$m_2 = \rho\,(R_1 + R_2 + R_a) + 2\,R_a^2(q - q^2) + R_1\,R_a(1-q) + R_2\,R_a\,q.$$
$$n_1 = \rho\,R_1\,(q + \tfrac{1}{2}) + \rho\,R_2\,(q - \tfrac{1}{2}) + \rho\,R_a\,q + R_1\,R_a\,q + 2\,R_a^2\,q\,(q - q^2).$$
$$n_2 = \rho\,R_1\,(q - \tfrac{1}{2}) + \rho\,R_2\,(q + \tfrac{1}{2}) + \rho\,R_a\,q + R_2\,R_a\,q + 2\,R_a^2\,q\,(q - q^2).$$
$$p_1 = \rho\,R_1\,(\tfrac{1}{2} - q) + \rho\,R_2\,(1\tfrac{1}{2} - q) + \rho\,R_a\,(1-q) + R_2\,R_a\,(1-q) + 2\,R_a^2\,q\,(1-q)^2.$$
$$p_2 = \rho\,R_1\,(1\tfrac{1}{2} - q) + \rho\,R_2\,(\tfrac{1}{2} - q) + \rho\,R_a\,(1-q) + R_1\,R_a\,(1-q) + 2\,R_a^2\,q\,(1-q)^2.$$
$$U = \rho\,R_a\,(R_1 + R_2) + R_1\,R_2\,(2\,\rho + R_a) + \rho^2\,(R_1 + R_2 + R_a) + 2\,R_a\,(q - q^2)\,[R_a\,(R_1 + R_2) + \rho\,(R_1 + R_2 + 2\,R_a) + 2\,R_a^2\,(q - q^2)].$$

Then the complete solution is—

$$C_0 = x - y + z - w.$$

$$= \frac{1}{U}\left(e \cdot 2\,W - L_7 \frac{d(x-y)}{dt} m_1 - L_8 \frac{d(z-w)}{dt} m_2 - L_3 \frac{dx}{dt} n_1 \right.$$
$$\left. - L_3 \frac{dz}{dt} n_2 + L_4 \frac{dy}{dt} \cdot p_1 + L_4 \frac{dw}{dt} \cdot p_2 \right)$$

$$= \frac{1}{U}\left(e \cdot 2\,W - L_7 \frac{dc_{07}}{dt} m_1 - L_8 \frac{dc_{08}}{dt} m_2 - L_3 \frac{dc_{03}}{dt} n_1 \right.$$
$$\left. - L_3 \frac{dc_{05}}{dt} n_2 - L_4 \frac{dc_{04}}{dt} p_1 - L_4 \frac{dc_{06}}{dt} \cdot p_2 \right) \quad . \quad (18)$$

where W has the same value as in the preceding section.

It is not possible to effect legitimately any further simplification; in general, although $\frac{dc_{03}}{dt}$ is very similar to $\frac{dc_{06}}{dt}$, and, indeed, has the same *average* value, yet their instantaneous equality would mean the constancy of c_{02} in R_2, a condition which is forbidden simply by the changing ohmic resistances. Similarly $\frac{dc_{04}}{dt}$ is very similar to $\frac{dc_{05}}{dt}$, and has the same average rate, but it is just their small instantaneous divergence which corresponds to the slight pulsation in the value of c_{01} in R_1; or, again, when differently grouped, the differences in the rates of change are the counterpart of the pulsation in the values of c_{07} and c_{08}.

Lastly, it may be added that although L_7 and L are much greater than L_3 and L_4, yet $\frac{dc_{03}}{dt}$, $\frac{dc_{04}}{dt}$, etc., are considerable, and much greater than $\frac{dc_{07}}{dt}$ and $\frac{dc_{08}}{dt}$, so that there is only a slight preference in retaining the latter rather than the former.

When, as is more usual, the two phases are wound on the same core, in place of the last term on the right-hand side of each of the four simultaneous equations we have—

$$- l_7 \cdot \frac{d(x-y)}{dt} - M\left(\frac{d(x-y)}{dt} - \frac{d(z-w)}{dt}\right)$$

$$+ l_7 \cdot \frac{d(x-y)}{dt} + M\left(\frac{d(x-y)}{dt} - \frac{d(z-w)}{dt}\right)$$

$$- l_8 \cdot \frac{d(z-w)}{dt} + M\left(\frac{d(x-y)}{dt} - \frac{d(z-w)}{dt}\right)$$

$$+ l_8 \cdot \frac{d(z-w)}{dt} - M\left(\frac{d(x-y)}{dt} - \frac{d(z-w)}{dt}\right)$$

In the final result for C_0 it is only necessary in (18) to write l_7 and l_8 for L_7 and L_8, and to add within the bracket a new term, viz. :—

$$+ (R_1 - R_2) R_a (1 - 2q) M \left(\frac{d c_{07}}{dt} - \frac{d c_{08}}{dt}\right).$$

Since this term disappears when $q = \frac{1}{2}$, it introduces no further change in the working formulæ at the moment when $q = \frac{1}{2}$.

When all inductive effects from the out-of-balance components are neglected—

$$c_{03} = x = e \cdot \frac{n_1}{U}, \qquad c_{05} = z = e \cdot \frac{n_2}{U},$$

$$-c_{04} = y = -e \cdot \frac{p_1}{U}, \qquad -c_{06} = w = -e \cdot \frac{p_2}{U},$$

$$(c_{03} + c_{04}) \text{ in one limb of the balancer} = x - y = e \cdot \frac{m_1}{U}.$$

$$(c_{05} + c_{06}) \text{ in the other limb of the balancer} = z - w = e \frac{m_2}{U}.$$

Or if—

$$f_1 = n_1 + p_2 = 2\rho R_1 + \rho R_a + R_1 R_a + 2 R_a^2 (q - q^2).$$
$$f_2 = n_2 + p_1 = 2\rho R_2 + \rho R_a + R_2 R_a + 2 R_a^2 (q - q^2).$$
$$(c_{03} + c_{06}) \text{ in } R_2 = x - w = e \frac{f_1}{U} = C_0 \cdot \frac{f_1}{2W}.$$
$$(c_{04} + c_{05}) \text{ in } R_1 = z - y = e \frac{f_2}{U} = C_0 \cdot \frac{f_2}{2W}.$$

By assigning any values to the resistances and to e the accuracy of the above is easily tested, and the exact equalisation of e in each circuit may be proved.

III. In the 4-phase case, neglecting any E.M.F.'s self-induced by the out-of-balance currents themselves, we have strictly, when $q = \frac{1}{2}$—

$$C_0 = e \cdot \frac{2W'}{U'},$$

where—

$$W' \text{ is now} = 2\rho (R_1 + R_2 + R_a) + 1\tfrac{1}{2} R_a (R_1 + R_2) + R_a^2 + \frac{R_a^2}{4\rho}\left(R_1 + R_2 + \frac{R_a}{2}\right),$$

and—

$$U' = 4\rho R_1 R_2 + \rho^2 (R_1 + R_2 + R_a) + 2\tfrac{1}{4} \rho R_a (R_1 + R_2) + 3 R_1 R_2 R_a + R_a^2 \left(R_1 + R_2 + \rho + \frac{R_1 R_2}{2\rho}\right) + \tfrac{5}{16} R_a^3 + \frac{R_a^3}{8\rho}\left(R_1 + R_2 + \frac{R_a}{4}\right).$$

Neglecting any E.M.F.'s self-induced in the armature, and taking

into account only the inductance of each limb of the balancer, viz., L_7 and L_8, the true expression for C_b is—

$$C_b = \frac{E_a\left(4\rho + 3R_a + \frac{R_a^2}{2\rho}\right) - \left[E_4 - L\left(\frac{di_7}{dt} - \frac{di_8}{dt}\right)\right]\left(R_a + \frac{R_a^2}{4\rho}\right)}{2W'},$$

E_4 being the intermediate E.M.F. of Fig. 6.

The second term of the numerator is practically negligible. Further—

$$2W' = \left(4\rho + 3R_a + \frac{R_a^2}{2\rho}\right)(R_1 + R_2 + R_a) - R_a^2\left(1 + \frac{R_a}{4\rho}\right),$$

so that C_b is slightly increased by the presence of the last term in the denominator, but approximately C_b may be again identified with—

$$\frac{E_a}{R_1 + R_2 + R_a}.$$

Lastly—

$$U' = \left(4\rho + 3R_a + \frac{R_a^2}{2\rho}\right)\left[R_1 R_2 + \frac{\rho}{4}(R_1 + R_2 + R_a) + \frac{R_a}{4}\left(R_1 + R_2 + \frac{R_a}{4}\right)\right] + \tfrac{1}{2}R_a(R_1 + R_2)(\rho + \tfrac{1}{4}R_a)$$

and as the last term is but small, the whole reduces very closely to—

$$C_0 = \frac{(R_1 - R_2)E_a}{2R_1R_2 + \frac{\rho}{2}(R_1 + R_2 + R_a) + \frac{R_a}{2}\left(R_1 + R_2 + \frac{R_a}{4}\right)},$$

or when the shunt current is taken into account we reach equation (15).

IV. In the 3-phase case when $q = \frac{1}{2}$—

$$C_0 = e \cdot \frac{2W'}{U'}$$

where—

$$2W' = 3\rho(R_1 + R_2 + R_a) + \tfrac{8}{3}R_a(R_1 + R_2) + 2R_a^2 + \frac{16}{27}\cdot\frac{R_a^2}{\rho}\left(R_1 + R_2\frac{R_a}{2}\right).$$

On the same assumptions as above—

$$C_b = \frac{E_a\left[3\rho + 2\left(1\frac{1}{3}R_a\right) + \frac{1}{3\rho}\left(1\frac{1}{3}R_a\right)^2\right]}{2W'}$$

a second term in the numerator being negligible.

But—

$$2\,W' = \left(3\rho + \frac{8}{3}\,R_a + \frac{16}{27} \cdot \frac{R_a^{\,2}}{\rho}\right)(R_1 + R_2 + R_a) - \frac{2}{3}\left(R_a^{\,2} + \frac{4\,R_a^{\,3}}{\rho}\right)$$

so that approximately again—

$$C_b = \frac{E_a}{R_1 + R_2 + R_a}.$$

Lastly, U′ is very closely—

$$= \left(3\rho + \frac{8}{3}\,R_a + \frac{16}{27} \cdot \frac{R_a^{\,2}}{\rho}\right)\Big[R_1\,R_2 + \rho 3\,(R_1 + R_2 + R_a) + \frac{R_a}{3}\left(R_1 + R_2 + \frac{1}{6} . R_a\right)\Big]$$

whence—

$$C_o = \frac{(R_1 - R_2)\,E_a}{2\,R_1\,R_2 + \frac{2}{3}\,\rho\,(R_1 + R_2 + R_a) + \frac{2}{3}\,R_a\,(R_1 + R_2 + \frac{1}{6} . R_a)}.$$

into account only the inductance of each limb of the balancer, viz., L_7 and L_8, the true expression for C_b is—

$$C_b = \frac{E_a\left(4\rho + 3R_a + \frac{R_a^2}{2\rho}\right) - \left[E_4 - L\left(\frac{di_7}{dt} - \frac{di_8}{dt}\right)\right]\left(R_a + \frac{R_a^2}{4\rho}\right)}{2W'},$$

E_4 being the intermediate E.M.F. of Fig. 6.

The second term of the numerator is practically negligible. Further—

$$2W' = \left(4\rho + 3R_a + \frac{R_a^2}{2\rho}\right)(R_1 + R_2 + R_a) - R_a^2\left(1 + \frac{R_a}{4\rho}\right),$$

so that C_b is slightly increased by the presence of the last term in the denominator, but approximately C_b may be again identified with—

$$\frac{E_a}{R_1 + R_2 + R_a}.$$

Lastly—

$$U' = \left(4\rho + 3R_a + \frac{R_a^2}{2\rho}\right)\left[R_1 R_2 + \frac{\rho}{4}(R_1 + R_2 + R_a) + \frac{R_a}{4}\left(R_1 + R_2 + \frac{R_a}{4}\right)\right] + \tfrac{1}{2}R_a(R_1 + R_2)(\rho + \tfrac{1}{4}R_a)$$

and as the last term is but small, the whole reduces very closely to—

$$C_0 = \frac{(R_1 - R_2)E_a}{2R_1R_2 + \frac{\rho}{2}(R_1 + R_2 + R_a) + \frac{R_a}{2}\left(R_1 + R_2 + \frac{R_a}{4}\right)},$$

or when the shunt current is taken into account we reach equation (15).

IV. In the 3-phase case when $q = \frac{1}{2}$—

$$C_0 = e \cdot \frac{2W'}{U'}$$

where—

$$2W' = 3\rho(R_1 + R_2 + R_a) + \tfrac{8}{3}R_a(R_1 + R_2) + 2R_a^2 + \frac{16}{27}\cdot\frac{R_a^2}{\rho}\left(R_1 + R_2\frac{R_a}{2}\right).$$

On the same assumptions as above—

$$C_b = \frac{E_a\left[3\rho + 2\left(1\frac{1}{3}R_a\right) + \frac{1}{3\rho}\left(1\frac{1}{3}R_a\right)^2\right]}{2W'}$$

a second term in the numerator being negligible.

But—

$$2\,W' = \left(3\rho + \frac{8}{3}\,R_a + \frac{16}{27}\cdot\frac{R_a^2}{\rho}\right)(R_1 + R_2 + R_a) - \frac{2}{3}\left(R_a^2 + \frac{4\,R_a^3}{\rho}\right)$$

so that approximately again—

$$C_b = \frac{E_a}{R_1 + R_2 + R_a}.$$

Lastly, U′ is very closely—

$$= \left(3\rho + \frac{8}{3}\,R_a + \frac{16}{27}\cdot\frac{R_a^2}{\rho}\right)\Big[R_1\,R_2 + \rho 3\,(R_1 + R_2 + R_a) + \frac{R_a}{3}\left(R_1 + R_2 + \frac{1}{6}.R_a\right)\Big]$$

whence—

$$C_o = \frac{(R_1 - R_2)\,E_a}{2\,R_1\,R_2 + \frac{2}{3}\,\rho\,(R_1 + R_2 + R_a) + \frac{2}{3}\,R_a\,(R_1 + R_2 + \frac{1}{6}\,.\,R_a)}.$$

Proceedings of the Thirty-eighth Annual General Meeting of the Institution of Electrical Engineers, held in the Rooms of the Royal Society of Arts, John Street, Adelphi, W.C., on Thursday evening, May 26, 1910—Mr. W. DUDDELL, F.R.S., Vice-President, in the chair.

The CHAIRMAN: Gentlemen, the meeting of the Institution, called for May 12th, was postponed owing to the death of His Majesty King Edward VII. I do not think I need say any words from this chair in eulogy of our late King, but I wish to read to you the following resolution which was passed by the Council at a special meeting:—

"That the Council of the Institution of Electrical Engineers, in special meeting assembled, hereby record their sense of the deep loss which the British Empire has sustained through the lamented death of His Majesty King Edward VII., and their sorrow that one who spent his life for the good of his people, and to whom his subjects were affectionately devoted, has been removed from the scene of his unremitting labours, and that a reign marked by unparalleled social, scientific, and industrial progress has thus been brought to a close.

"The Council humbly beg permission to express to His Majesty King George V., the Queen Mother, and to the Members of the Royal Family, their sincere condolence and sympathy, and, further, to lay before His Majesty the assurance of their unswerving loyalty and devotion, and their earnest wishes that he may, with Her Majesty Queen Mary, long be spared to reign in happiness and peace over a loving and united people."

Gentlemen, I will ask you to confirm that motion standing, and in silence.

The resolution was carried in silence, all present standing.

The minutes of the Ordinary General Meeting held on May 5, 1910, were taken as read, and confirmed.

The CHAIRMAN: I regret to say that our President has written saying that he is still unwell, and unable to attend this evening.

The next business that we have to transact is to appoint scrutineers of the ballot for the Council election. As about one thousand papers have to be counted, I suggest that four scrutineers should be appointed, and I suggest that Mr. W. A. Chamen, Mr. R. J. Wallis Jones, Mr. C. S. Thomson, and Mr. R. W. Hughman act in that capacity.

The suggestion was agreed to.

The CHAIRMAN: As there is such a large number of papers to be dealt with, I will request the scrutineers to be good enough to start their work at once. I will ask them to count the papers, and to let me have a signed statement of the number of votes for each individual, so that I may announce them to the meeting. I ask them at the conclusion of their labours to put the ballot papers into an envelope and to seal them up in case any question should afterwards arise. I believe the usual course is to deposit that envelope with the Secretary of the Institution. If the meeting has no objection to this course being taken, I will now ask the scrutineers to commence their work.

The list of candidates for election into the Institution was taken as read, and it was ordered that it should be suspended.

The following list of transfers was announced as having been approved by the Council:—

TRANSFERS.

From the class of Associate Members to that of Members:—

Herbert C. Gunton.
Albert Henry W. Marshall.
Charles E. C. Shawfield.
Charles Edward Smith.
Frank E. Stanley.
Thomas Parry O. Yale.

From the class of Associates to that of Members:—

Donald S. Barton.
Francis Lydall.
Henry J. Spencer.

From the class of Associates to that of Associate Members:—

Frederick H. G. Goodwin.
James S. Smith.
Andrew Cyril Weber.

From the class of Students to that of Associate Members:—

John William Bell.
Arthur B. Cartland.
Harry Corney.
George Dearle.
Alfred Geo. Ellis.
John R. Gillman.
Kenneth Geo. S. Hatfield.
Archibald C. Lock.

From the class of Students to that of Associate Members (*contd.*) :—

Camille N. Mathieu.
Charles J. Melbourne.
Clifford G. Rattray.
Godfrey Jas. D. Scott.
George F. Sills.
Henry J. Troughton.
Walter D. Wilson.

Messrs. R. Grigg and C. W. Smith were appointed scrutineers of the ballot for the election of new members, and, at the end of the meeting, the following were declared to have been duly elected :—

ELECTIONS.

As Member.

Adolphe Alfred Dion.
Alfred Hands.

As Associate Members.

James Grey Bell.
James S. Brown.
Sune H. Busch.
Percy J. Childs.
William F. Duncan.
Hugo V. Flinn.
John Wesley Fraser.
Sidney Chas. Hackney.
Francis J. O. Howe.
J. Walter Miles.
Joseph C. H. Morby.
Arthur J. Newman.
Nicolo Pensabene-Perez.
Arthur J. Rayner.
Alex. M. Robertson.
George Wm. Shearer.
Deane H. Slack.
Laurance W. Swainson.
John T. Tattersall.
Harold Wm. Tyler.
Archibald L. Veitch.
Alfred Geo. Watson.
James Hope Wright.

As Associate.

William Henry Hunter.

As Students.

Richard M. Clark.
James H. Enion.
José Vaz M. Gomes.
Harold E. Gough.
Stanley M. Hill.
Norman G. Kapp.
Reginald Otto Kapp.
Geo. William McCall.
Domingos J. Martinos.
Ashley Plowman.
Balkrishna B. Pradhan.
Harold Rider.
Herbert Shannon.
John Slevin.
William M. Slevin.
Richard Stafford.
Herbert A. Steytler.
Herbert Tetlow.
Gordon H. Tilly.
Prayag N. Varman.

Donations to the *Library* were announced as having been received since the last meeting from The Adams Manufacturing Company, Ltd.,

the Comte de Baillehache, T. H. Churton, The Colliery Guardian Company, Ltd., A. G. Collis, A. Constable & Co., Ltd., U. Crudeli, E. Haanel, A. W. Marshall, T. E. Murray, L. Oulton, W. H. Patchell, E. & F. N. Spon, Ltd., to whom the thanks of the meeting were duly accorded.

Annual Report.

The Chairman: The next matter on the agenda is the annual report, a copy of which I believe is in the hands of all the members here present.

The Chairman then proceeded to read the Annual Report.

REPORT OF THE COUNCIL FOR PRESENTATION TO THE ANNUAL GENERAL MEETING OF MAY 26, 1910.

At this, the thirty-eighth Annual General Meeting of the Institution of Electrical Engineers, the Council present to the Members their Report for the Session 1909–10.

Death of His Majesty King Edward VII.

The Institution shares in the public grief at the irreparable loss sustained by the nation through the death of His Majesty King Edward VII., which occurred on the 6th of this month. A vote of condolence and loyalty has been passed by the Council and transmitted to the Home Secretary to be forwarded to His Majesty King George.

Growth of the Institution.

Since the last Annual General Meeting, 505 proposals for election have been considered, and there have been elected 9 Members, 214 Associate Members, 6 Associates, and 233 Students.

39 Associate Members and 12 Associates have been transferred to the class of Members, 28 Associates and 117 Students to the class of Associate Members, and 3 Students to the class of Associates.

The changes in the List of Members since the last Annual General Meeting are shown in the following table :—

	1909.	1910.
Honorary Members	7	7
Members	1,136	1,172
Associate Members	2,375	2,628
Associates	1,036	939
Students	1,438	1,368
Foreign Members	105	104
Total	6,097	6,218

Members Deceased.

Among well-known members who have died since the last Annual General Meeting are Major Philip Cardew, a Past Vice-President,

Mr. John Oldham, Local Honorary Secretary and Treasurer for Uruguay from 1886 to 1902, Sir Charles Todd, K.C.M.G., F.R.S., Local Honorary Secretary and Treasurer for South Australia from 1881 to 1906, Mr. Shelford Bidwell, F.R.S., and Mr. Hugh Erat Harrison, B.Sc., Past-Members of Council.

The complete list of those who have died during the past Session is as follows:—

Members.

Shelford Bidwell, F.R.S.	John Oldham.
Major Philip Cardew, R.E. (ret.).	Arthur Warren Peirce.
Oswald Haes.	John Rance.
Hugh Erat Harrison.	James Reid.
Musgrave Heaphy.	Charles John Robertson.
Francis Hastings Medhurst.	Sir Charles Todd, K.C.M.G.
	Alfred Allen Whitlock.

Associate Members.

Walter Herbert Beilby.	Lionel Eugene Radcliffe.
Alfred Alexander Cahen.	Henry J. Rogers.
Louis du B. Hugo.	Thomas Rowe.
Herbert John Mills.	Arthur Denby Smith.
James Nicolson.	Percival Storey.

Associates.

Henry Bligh Forde.	Alfred Charles Weaver.
Edmund Lewis Robinson.	Charles E. Winter.

Students.

Arthur Forrest Henderson.	Vasudeo S. Padhye.

Charles J. Tyler.

Foreign Members.

Jules Gramaccini.	S. Kanda.

Biographical notices of the deceased members will be found in the *Journal.*

Resignations.

6 Members, 28 Associate Members, 16 Associates, 64 Students, and 1 Foreign Member have resigned since the last Annual General Meeting.

Meetings and Papers.

During the past Session 15 General Meetings, 2 Special General Meetings, and 19 Council Meetings have been held. The usual Standing Committees have met regularly throughout the Session, and several Occasional Committees appointed by the Council for the consideration of special matters have also met, the total number of Committee Meetings held during the Session being 120.

There have been 45 meetings of Local Sections, viz., 7 at Birmingham, 7 at Dublin, 7 at Glasgow, 11 at Manchester, 6 at Newcastle, and 7 at Leeds and Sheffield.

The Annual Dinner of the Institution took place at the Hotel Cecil, London, on December 8th, 1909. A report of the proceedings will be found in the *Journal*, vol. 44, p. 269.

Annual Dinners and other social functions were held at Birmingham, Dublin, Glasgow, Leeds, Manchester, and Newcastle, which were well attended by members and guests, and at which several Members of Council were present.

The following is the list of papers for the Session, with the names of the authors and the places where read :—

TITLE.	AUTHOR.	WHERE READ.
Inaugural Address of President.	Dr. G. KAPP.	London.
Chairman's Address.	Prof. W. BROWN, B.Sc.	Dublin.
Chairman's Address.	R. K. MORCOM.	Birmingham.
Chairman's Address.	E. G. TIDD.	Glasgow.
Chairman's Address.	S. J. WATSON.	Manchester.
Chairman's Address.	Prof. H. STROUD.	Newcastle.
Chairman's Address.	W. M. ROGERSON.	Leeds.
"A Telephone Relay."	S. G. BROWN, Member.	London.
"Hydro-electric Installations of Sweden."	A. V. CLAYTON, Member.	London.
"Balancers for Three-wire Systems."	A. G. COOPER, Associate Member.	Manchester.
"Some Properties of Switch and Transformer Oils."	W. P. DIGBY, Associate Member, and D. B. MELLIS.	Manchester.
"Efficiency of Short-spark Methods of Generating Electrical Oscillations."	W. H. ECCLES, D.Sc., and A. J. MAKOWER, M.A., Associate Member.	London.
"Second Kelvin Lecture."	Prof. J. A. EWING, C. B., F. R. S., Member.	London.
"An Electrical Safety System for Use in Mines."	H. J. FISHER, Associate Member.	Newcastle.
"Some Quantitative Measurements in Connection with Radiotelegraphy."	Dr. J. A. FLEMING, M. A., F. R. S., Member.	London.
"Progress of Electric Braking on the Glasgow Corporation Tramway System."	A. GERRARD, Associate Member.	London and Glasgow.
"The Influence of Various Cooling Media upon the Rise in Temperature of Soft Iron Stampings."	R. D. GIFFORD, M.Sc., Student.	Birmingham.

TITLE.	AUTHOR.	WHERE READ.
"The Present Aspect of Electric Lighting."	H. W. HANDCOCK and A. H. DYKES, Members.	London, Birmingham, and Manchester.
"Modern Electric Time Service."	F. HOPE-JONES, Member.	London.
"Standardisation of Fuses."	H. W. KEFFORD.	Birmingham.
"Continuous-current Boosters and Balancers."	W. A. KER.	Glasgow.
"Research on Metallic Filament Lamps."	F. H. R. LAVENDER, M.Sc., Student.	Birmingham.
"Notes on Methods and Practice in the German Electrical Industry."	L. J. LEPINE and A. R. STELLING, Students.	London, Birmingham, and Manchester.
"Some Experiments on Single and Stranded Low-tension Fuses."	W. T. MACCALL, Associate Member.	Sheffield.
"Recent Developments in the Transmission of Electrical Energy at High Tensions on Overhead Lines."	Prof. E. W. MARCHANT, D.Sc., Member, and E. A. WATSON, M.Sc., Student.	Manchester.
"On the Use of the Flicker Photometer for Differently Coloured Lights."	H. MORRIS-AIREY, M.Sc.	Newcastle.
"An Investigation as to the most Economical Vacuum in Electric Power Stations employing Steam Turbines and Cooling Towers."	R. M. NEILSON.	Glasgow.
"Some Notes on Standardisation of Electrical Machines."	R. ORSETTICH, Member.	Birmingham and Glasgow.
"Rating and Testing of Motors for Intermittent Working."	Dr. R. POHL, Associate Member.	Leeds.
"The Testing of Rubber for Electrical Work."	Prof. A. SCHWARTZ, Member.	Manchester.
"An Improved Type of Point Controller for Electric Tramways."	J. P. TIERNEY, Associate Member.	Dublin.
"The Design of Turbo Field Magnets for Alternate-current Generators, with Special Reference to Large Units at High Speeds."	M. WALKER, Member.	London.
"Short-circuiting of Large Electric Generators and the Resulting Forces on Armature Windings."	M. WALKER, Member.	London and Manchester.

Title.	Author.	Where Read.
"The Electric Ignition of Internal Combustion Engines.'	J. W. Warr, Associate Member.	Manchester.
"Losses off Transmission Lines due to Brush Discharge, with Special Reference to Direct Current."	E. A. Watson, Student.	London.
"Metallic Filament Lamps: their possible Beneficial Effect on Supply Undertakings."	G. Wilkinson, Member, and R. McCourt, Associate Member.	Leeds.
"Telephones."	L. E. Wilson.	Manchester.
"Earthed *v.* Insulated Neutrals in Colliery Installations."	W. W. Wood, Associate.	London and New castle.
"Some Notes on Overhead Line Construction."	W. B. Woodhouse, Associate Member.	Leeds.
"Commutation Phenomena and Magnetic Oscillations occurring in Direct-current Machines."	G. W. Worrall, M.Sc., Associate Member.	Birmingham.
"Equitable Charges for Tramway Supply."	H. E. Yerbury, Member.	London, Birmingham, Glasgow, Manchester, and Sheffield.

In addition to the above-mentioned papers read at meetings the following have been accepted for printing in the *Journal*:—

Title.	Author.
"On Magnetic Testing of Iron with Alternating Current."	Albert Campbell, B.A., Associate Member.
"The Examination of Water by Electrical Methods."	W. P. Digby, Associate Member.
"The Theory of the Dynamometer Wattmeter."	C. V. Drysdale, D.Sc., Member.
"Graphical Treatment of the Zigzag and Slot Leakage in Induction Motors."	R. E. Hellmund.
"Experimental Determination of the Moment of Inertia of a Continuous-current Armature."	Dr. G. Kapp, President.
"Dimensions of Single-phase Core and Shell Transformers, with Copper and Iron Circuits of Uniform Rectangular Cross-section."	A. R. Low, Associate Member.
"The Relation between the Stator and Rotor Circuits of the Single-phase Induction Motor."	C. F. Smith, Member.
"The Arrangement of Experimental Electrical Circuits for Laboratories."	W. P. Steinthal, M.Sc., Associate Member.
The Metal Tungsten as 'Valve' Electrode."	L. H. Walter, M.A., Associate Member.

"The Production, Measurement, and Effect of Variable Wave Form." L. W. WILD, Member.

SCHOLARSHIPS.

The Council have awarded a Salomons Scholarship of the value of £50 to Brian Charles Clayton, of King's College; and David Hughes Scholarships of the value of £50 each, to George Wood Pearce Page, of the Central Technical College, and to Archibald Davidson Peacock, of University College.

PREMIUMS.

The following premiums for papers and communications have been awarded by the Council this year. In accordance with precedent, in deciding upon these awards the Council have not taken into account papers contributed by present members of Council.

The INSTITUTION PREMIUM, value £25,

to Mr. Miles Walker, for his two papers, "Short Circuiting of Large Electrical Generators and the resulting Forces on Armature Windings," and "The Design of Turbo Field Magnets for Alternate-current Generators, with Special Reference to Large Units at High Speeds."

The PARIS ELECTRICAL EXHIBITION PREMIUM, value £10,

to Professor A. Schwartz, for his paper, "The Testing of Rubber for Electrical Work."

The FAHIE PREMIUM, value £10,

to Mr. S. G. Brown, for his paper, "A Telephone Relay."

A PREMIUM, value £10,

to Messrs. W. P. Digby and D. B. Mellis, for their paper, "Some Properties of Switch and Transformer Oils."

A PREMIUM, value £10,

to Mr. G. W. Worrall, for his paper, "Commutation Phenomena and Magnetic Oscillations occurring in Direct Current Machines."

A PREMIUM, value £5,

to Mr. F. Hope-Jones, for his paper, "Modern Electric Time Service."

A PREMIUM, value £5,

to Mr. F. H. R. Lavender, for his paper, "Research on Metallic Filament Lamps."

A PREMIUM, value £5,

to Mr. Albert Campbell, for his Original Communication, "On Magnetic Testing of Iron with Alternating Current."

A Premium, value £5,

to Mr. C. F. Smith, for his Original Communication, "The Relation between the Stator and Rotor Circuits of the Single-phase Induction Motor."

A Premium, value £5,

to Mr. L. W. Wild, for his Original Communication, "The Production Measurement, and Effect of Variable Wave-Form."

Students' Premiums.

A First Students' Premium, value £10,

to Mr. R. C. Plowman, for his paper, "Isolated Electrical Plants."

A Second Students' Premium, value £5,

to Mr. A. P. Young, for his paper, "Theory and Design of Current Transformers."

Three Students' Premiums, each of the value of £5,

to Messrs. P. J. Cottle and J. A. Rutherford, for their paper, "Collection of Current at High Peripheral Speeds"; to Messrs. P. Kemp and W. A. Stephens, for their paper, "High Tension Spark Discharge in Air"; to Mr. W. H. Young, for his paper, "The Localisation of Breaks in Submarine Cables."

Willans Premium.

The selection for the fifth triennial Willans Premium fell this year to the Council, who have awarded the premium to Mr. J. H. Rider for his paper entitled "The Electrical System of the London County Council Tramways," read before the Institution in 1909.

Students' Section.

At the opening meeting of the session an address to the students was delivered by Mr. J. H. Rider on the subject of "The Importance of Attention to Detail."

Ten meetings of the Students' Section have been held in the Library of the Institution, at which papers were read and discussed.

The Students' Committee organised a visit to Berlin in the summer of 1909, when the following works and places of interest were visited: The Allgemeine Elektricitäts Gesellschaft; the Electrical Engineering Department of the Königliche Technische Hochschule, Charlottenburg; Siemens-Schuckert werke; Dr. Cassirer & Co.; the Physikalisch-Technische Reichsanstalt; Bergmann Elektrizitäts-werke A.G.; the Elberfeld Barmen Mono-Rail Electric Railway. Thirty-eight Students took part in the tour, which was very successful.

The Annual Dinner of the Students' Section, held on January 26, 1910, was well attended.

The Glasgow and Manchester Branches of the Students' Section

have each completed a successful session, having held six and nine meetings respectively. Visits were made to various works by the kind permission of the firms concerned.

The Institution Building.

The structural alterations necessary to adapt the building to the requirements of the Institution have been in progress since August of last year. It is expected that the offices will shortly be transferred to the building, and that the Lecture Theatre, Library, and members' rooms will be ready in time for the opening of the new session.

"Science Abstracts."

The volumes for 1909 were of nearly the same size as those for 1908, the number of abstracts and references being 2,161 in the Physics Section and 1,191 in the Electrical Engineering Section.

The British Electrotechnical Committee.

The British Committee for 1910 is constituted as follows :—

The Council for the time being of the Institution, with the addition of Mr. K. Edgcumbe, Mr. S. Z. de Ferranti, Mr. C. le Maistre, Mr. H. W. Miller, The Lord Rayleigh, O.M., F.R.S., Captain H. R. Sankey, R.E. (ret.), Mr. C. P. Sparks, Mr. A. P. Trotter, and Mr. E. B. Vignoles.

In view of the removal to the new building it was felt that it would be an advantage to transfer the work of the Committee to the Institution. The Committee having given their consent, the transfer was effected in January of this year, and the work is now carried on in the offices of the Institution.

During the last Session the Committee and its Sub-Committees on Nomenclature and on Symbols have held eight meetings and have made satisfactory progress.

An informal meeting of the Electrotechnical Committees of the various countries will take place at Brussels next August. This will afford an opportunity for an exchange of views, and will considerably facilitate the work of preparation of the several Committees for the official International Meeting arranged to take place in Berlin in 1911.

Wiring Rules.

The revision in progress has been carried further than was at first intended. By the kindness of Dr. R. T. Glazebrook, F.R.S., Director of the National Physical Laboratory, tests are being made with reference to certain data in the Rules. It is hoped that the revised edition will be ready before the end of the year.

Model General Conditions for Contracts.

The Model General Conditions for Contracts which were issued in 1903 are under revision. In this work the Council have had the

benefit of the co-operation of The Cable Makers Association, The Electrical Contractors Association, The Incorporated Association of Electric Power Companies, The Incorporated Municipal Electrical Association, The National Electrical Manufacturers Association, The Tramways and Light Railways Association, all of which have appointed representatives to serve on the Committee carrying out the work of revision.

Professional Conduct.

The Council have decided to adopt the Regulations relating to Professional Conduct recently incorporated in the By-Laws of the Institution of Civil Engineers, and subject to the proposal receiving the sanction of a Special General Meeting of Members and Associate Members, these Regulations will be embodied in the Articles of Association and be applicable to members of all classes. The Regulations are as follows:—

Every member of the Institution shall observe and be bound by the following regulations:—

1. He shall act in all professional matters strictly in a fiduciary manner with regard to any clients whom he may advise, and his charges to such clients shall constitute his only remuneration in connection with such work, except as provided by Clause 4.
2. He shall not accept any trade commissions, discounts, allowances, or any indirect profit in connection with any work which he is engaged to design or to superintend, or with any professional business which may be entrusted to him.
3. He shall not, while acting in a professional capacity, be at the same time, without disclosing the fact in writing to his clients, a director or member of, or a shareholder in, or act as agent for, any contracting or manufacturing company or firm or business with which he may have occasion to deal on behalf of his clients, or have any financial interest in such a business.
4. He shall not receive, directly or indirectly, any royalty, gratuity, or commission on any patented or protected article or process used on work which he is carrying out for his clients, unless and until the receipt of such royalty, gratuity, or commission, has been authorised in writing by those clients.
5. He shall not improperly solicit professional work, either directly or by an agent, nor shall he pay, by commission or otherwise, any person who may introduce clients to him.
6. He shall not be the medium of payments made on his clients' behalf to any contractor or business firm (unless specially so requested by his clients), but shall only issue certificates or recommendations for payment by his clients.

Any alleged breach of these regulations or any alleged professional misconduct by a Corporate Member which may be brought before the

Council, properly vouched for and supported by sufficient evidence, shall be investigated, and if proved shall be dealt with by the Council either by expulsion of the offender from the Institution or in such other manner as the Council may think fit.

Examinations for Associate Membership.

A Committee has been appointed by the Council to consider, and report on, the question of an examination for Associate Membership.

Articles of Association.

As no alteration has taken place in the Articles of Association for the past five years, a Committee has been appointed to consider and to report whether any alterations are necessary, and any suggestions which the members may desire to make will be welcome.

Electric Lighting Act, 1909.

The Council carefully considered the provisions of the Electric Lighting Acts (Amendment) Bill (1909), and in May, 1909, addressed a letter to the Board of Trade with reference to several of the clauses. As a result, a deputation of the Council, consisting of Mr. W. M. Mordey, then President, Mr. J. E. Kingsbury, Mr. W. H. Patchell, Mr. A. Siemens, Mr. J. F. C. Snell, and Mr. A. A. Campbell Swinton, was received by the Board.

It was pointed out in the written communication, and emphasised by the deputation, that the Audit Clause in the Bill rendered interference with the conduct of an electrical business possible, and enabled the auditors of the Board to dictate the commercial policy of the business, a power which Parliament never intended to give. It was urged that the duties of the auditors should be restricted to seeing that the requirements of the Board of Trade were complied with as to the proper keeping and presenting of the accounts, and it was recommended that the clause should apply to local authorities as well as to companies. The clause did not receive the sanction of Parliament.

Electricity in Mines.

At the end of 1909 the Council were informed by the Home Office Committee appointed to consider the Rules for the Use and Installation of Electricity in Mines that they would be pleased to consider any evidence or papers bearing on the subject-matter of their inquiry which the Council might wish to submit. By means of notices in the technical press it was made known that the Council had the matter under consideration and invited observations from those interested. A number of suggestions were received, which were carefully considered, and subsequently a letter embodying the Council's views and recommendations was forwarded to the Committee. Mr. W. H. Patchell also attended at the Home Office and gave evidence on behalf of the Council.

Electricity in Textile Mills.

A Committee appointed by the Council to report on the question of electrical driving in textile mills are at present engaged in collecting the data available in collaboration with the Local Sections interested.

Building Fund.

The attention of members generally is called to this Fund. The Council hope that there will be a large increase in the number of contributors, and they wish to point out the importance, in the aggregate, of even small annual subscriptions.

Benevolent Fund.

The Committee of Management report that the Benevolent Fund of the Institution shows a satisfactory increase for the past year. On December 31, 1909, the capital account of the Fund stood at £3,500, as compared with £3,000 at the end of 1908. The donations to the Fund in 1909 include one of £25 from the Committee of the Electrical Engineers' Ball. The Council desire to acknowledge their indebtedness to the generosity of these and other donors and subscribers who have supported the Fund. Grants in aid amounting to £77 were made during 1909. The accounts for 1909 will be found on pages 758 and 759.

The Wilde Benevolent Trust Fund stands at £1,744 16s. One grant in aid of £25 was made from the income of the Fund during 1909.

Annual Accounts.

The Report of the Hon. Treasurer, Mr. Robert Hammond, is as follows:—

Income and Expenditure.—The balance carried to the General Fund at the end of 1909, being excess of income over expenditure, was £3,283 3s. 11d., as compared with £3,253 9s. 3d. for 1908, an increase of £29 14s. 8d. In this comparison no account is taken of outlays in connection with the acquisition of the Institution Building.

Balance Sheet.—The balance sheet sets out the total investments other than the investments of the Trust Funds. It will be seen that the total assets amount to £84,906 17s. 3d., against which are to be set liabilities amounting to £29,081 2s. 3d., leaving as the net assets of the Institution £55,825 15s. This amount is almost entirely locked up in the acquisition of the lease of the Institution Building, in the structural alterations, and in the expenses incurred prior to occupation.

The investments in stocks and shares included in the above appear in the accounts at cost price with a book value of—

	£	s.	d.
General Fund	3,270	10	1
Kelvin Lecture Fund...	862	10	10
	£4,133	0	11

and their value at the current market prices on April 23, 1910, was £3,750 4s. 10d.

Trust Funds.—No alteration has taken place in these three Funds during the year under consideration.

Life Compositions.—This Fund has been increased during the year by £31 10s., and stands at £5,613 3s., which amount now figures in the accounts as a loan to the Building Fund, the investments of the Fund having all been realised.

Entrance Fees Fund.—An increase is shown of £764 2s. This amount, together with the balance of £1,437 6s. 7d. brought forward from 1908, has been transferred to the Building Fund.

Building Fund.—In consequence of the acquisition of the Lease of the Institution Building, the constitution of this account differs materially from that set out in preceding years. The investments have all been realised, and the Fund has been augmented as follows: (*a*) permanently, by transfer of £2,201 8s. 7d. from the Entrance Fees Fund, and by revenue from the Tothill Street property, subscriptions, donations, dividends, and sundry other items, £1,234 7s. 5d.; (*b*) temporarily by loans, on mortgage from the Economic Life Assurance Society £26,000, from Life Compositions Fund £5,613 3s., and from General Fund £5,582 5s. 11d. This makes a total increase of £40,631 4s. 11d., and the Fund now stands as follows:—

	£	s.	d.
Cost of the Lease of the Institution Building, including Structural Alterations and Expenses during the same, Mortgage Expenses, Loss on Sale of Securities	57,124	2	4
Tothill Street Property	19,260	17	1
	£76,384	19	5

General Fund.—This Fund has increased to the extent of £3,283 3s. 11d. during the past year, and now stands at £10,135 10s. 8d.

Summary.—The increases of the Funds during the year have been as follows:—

	£	s.	d.
Entrance Fees...	764	2	0
Building Fund	1,234	7	5
General Fund	3,283	3	11
	£5,281	13	4

LIBRARY.

The Council have now acquired 1,444 out of the 1,623 works which were reported to be wanting to complete the Institution's collection of electrotechnical literature. In addition to these, 67 new books have been purchased since May 20, 1909, and 220 books and pamphlets have been presented by members, publishers, and kindred societies. The total number of readers during the past twelve months was 614, of whom 39 were non-members.

APPENDIX TO REPORT.

TRANSACTIONS, PROCEEDINGS, ETC., RECEIVED BY THE INSTITUTION.

BRITISH.

British Association for the Advancement of Science, Reports.
Cambridge Philosophical Society, Proceedings.
Chartered Institute of Patent Agents, Transactions.
Civil and Mechanical Engineers' Society, Transactions.
Faraday Society, Transactions.
Greenwich Magnetical and Meteorological Observations.
Incorporated Institution of Automobile Engineers, Proceedings.
Illuminating Engineering Society, Transactions.
Incorporated Municipal Electrical Association, Proceedings.
Institute of Chemistry, Proceedings.
Institute of Marine Engineers, Transactions.
Institute of Metals, Journal.
Institution of Civil Engineers, Proceedings.
Institution of Engineers and Shipbuilders in Scotland, Transactions.
Institution of Mechanical Engineers, Proceedings.
Institution of Mining and Metallurgy, Transactions and Bulletins.
Institution of Naval Architects, Transactions.
Institution of Post Office Electrical Engineers, Papers.
Iron and Steel Institute, Journal.
Liverpool Corporation Tramways, Annual Reports.
Liverpool Engineering Society, Proceedings.
Manchester Literary and Philosophical Society, Memoirs and Proceedings.
Manchester School of Technology, Journal.
National Physical Laboratory Reports, and Collected Researches.
North-East Coast Institution of Engineers and Shipbuilders, Transactions.
North of England Institute of Mining and Mechanical Engineers, Transactions.
Physical Society, Proceedings.
Röntgen Society, Journal.
Royal Dublin Society, Scientific and Economic Proceedings.
Royal Engineers' Institute, Proceedings.
Royal Institution, Proceedings.
Royal Meteorological Society, Quarterly Journal.
Royal Scottish Society of Arts, Transactions and Journal.
Royal Society, Philosophical Transactions and Proceedings.
Royal Society of Arts, Journal.
Royal Society of Edinburgh, Transactions and Proceedings.

Royal United Service Institution, Journal.
Society of Chemical Industry, Journal.
Society of Engineers, Proceedings.
Surveyors' Institution, Transactions and Professional Notes.
Tramways and Light Railways' Association, Official Circular.

COLONIAL.

Canadian Society of Civil Engineers, Transactions.
Engineering Association of New South Wales, Proceedings.
Engineering Society of Toronto, Transactions.
Indian Telegraph Department, Administration Reports.
Nova Scotia Institute of Science, Transactions and Proceedings.
Royal Society of Queensland, Proceedings.
Royal Society of Victoria, Proceedings.
South Australia, Meteorological Observation Reports.
Sydney University of Engineering, Proceedings.

AMERICAN.

American Academy of Arts and Sciences, Proceedings.
American Institute of Electrical Engineers, Transactions and Proceedings.
American Electrochemical Society, Transactions.
American Institute of Mining Engineers, Transactions and Bi-Monthly Bulletin.
American Philosophical Society, Proceedings.
American Society of Civil Engineers, Proceedings.
American Society of Mechanical Engineers, Transactions and Proceedings.
Bureau of Standards, Washington, Bulletin.
Engineers' Club of Philadelphia, Proceedings.
Franklin Institute, Journal.
Illuminating Engineering Society, N. S. Transactions.
Ordnance Department of the United States, Notes.
Philadelphia Electrical Bureau, Annual Reports.
Smithsonian Institution, Reports.
U.S. Official Patent Gazette.
Western Society of Engineers, Journal.

AUSTRIAN.

Kaiserliche Akademie der Wissenschaften, Wien, Sitzungsberichte.

BELGIAN.

Association des Ingénieurs Électriciens sortis de l'Institut Electro-technique Montefiore, Bulletin.
Société Belge d'Électriciens, Bulletin.

DUTCH.

Koninklijk Institut van Ingenieurs, Tijdschrift.
Koninklijke Akademie van Wetenschappen, Amsterdam, Proceedings.

FRENCH.

Académie des Sciences, Comptes Rendus Hebdomadaires des Séances.
Bureau des Longitudes, Annuaire.
Société des Anciens Élèves des Ecoles Nationales d'Arts et Metiers Bulletin Technologique.
Société des Ingénieurs Civils, Mémoires.
Société Française de Physique, Bulletin des Séances.
Société Internationale des Électriciens, Bulletin.
Société Scientifique Industrielle de Marseille, Bulletin.

GERMAN.

Physikalische Technische Reichsanstalt, Abhandlungen.
Schiffbautechnische Gesellschaft, Jahrbuch.
Verein Deutscher Ingenieure, Zeitschrift.
Verein zur Beförderung des Gewerbfleisses, Verhandlungen.

ITALIAN.

Associazione Elettrotecnica Italiana, Atti.
Reale Accademia dei Lincei, Atti e Memorie.

SWEDISH.

K. Svenska Vetenskaps-Akademien, Arkiv för Matematik, etc.

SWISS.

Association Suisse des Electriciens, Annuaire, et Bulletin.

LIST OF PERIODICALS RECEIVED BY THE INSTITUTION.

BRITISH.

Aero.
Automobile Owner.
Cassier's Magazine.
Central.
Colliery Guardian.
Electrical Bulletin.
Electrical Engineer.
Electrical Engineering.
Electrical Field.
Electrical Industries.
Electrical Magazine.
Electrical Review.
Electrical Times.
Electrician.
Electricity.
Electron.
Engineer.
Engineering.
Engineering Magazine.
Engineering Review.
English Mechanic.
Illuminating Engineer.
Illustrated Official Journal, Patents.
International Marine Engineering.
Iron and Coal Trades Review.
Light Railway and Tramway Journal.
Mechanical Engineer.
Mining Journal.
National Telephone Journal.
Nature.
Page's Weekly.
Philosophical Magazine.
Post Office Electrical Engineers' Journal.
Railway News.
Railway Times.
Royal Engineers' Journal.
Scientific Monthly.
Tramway and Railway World.
Vulcan.

COLONIAL.

Australian Mining Standard.

Australian Official Journal of Patents.
Canadian Machinery.

AMERICAN.

American Journal of Science.
Electric Journal.
Electric Railway Journal.
Electrical Review and Western Electrician.
Electrical World.
Engineering News.
India Rubber World.
Journal of the Telegraph.
Metallurgical and Chemical Engineering.
Physical Review.
Scientific American.
Telephony.
Terrestrial Magnetism and Atmospherical Electricity.

AUSTRIAN.

Elektrotechnik und Maschinenbau.

DANISH.

Teknisk Tidsskrift.

DUTCH.

De Ingenieur.

FRENCH.

Archives des Sciences Physiques et Naturelles.
Électricien.
Houille Blanche.
Industrie Électrique.
Journal de Physique.
Journal Télégraphique.
Lumière Électrique.
Mois Scientifique et Industriel.
Portefeuille Économique des Machines.
Revue Électrique.

GERMAN.

Annalen der Elektrotechnik.
Annalen der Physik.

Annalen der Physik, Beiblätter.
Elektrische Kraftbetriebe und Bahnen.
Elektrotechnische und Polytechnische Rundschau.
Elektrotechnische Zeitschrift.
Elektrotechnischer Anzeiger.
Fortschritte der Elektrotechnik.
Glückauf.
Jahrbuch der Elektrochemie.
Physikalische Zeitschrift.
Zeitschrift für Elektrochemie.
Zeitschrift für Instrumentenkunde.

ITALIAN.

L'Elettricista.
L'Elettricita.
Giornale del Genio Civile.
Il Nuovo Cimento.

SPANISH.

La Ingenieria.
Revista Electro-Industrial.

SWISS.

Schweizerische Elektrotechnische Zeitschrift.

The Institution of

STATEMENT OF INCOME AND
ENDED 31st

Dr.

EXPENDITURE.

				£	s.	d.	£	s.	d.
To MANAGEMENT :—									
Salaries ...				1,911	14	0			
Accountants' Fees				21	0	0			
Printing, Stationery, and Addressing				515	5	5			
Postage ...				827	6	9			
Telephone				28	4	2			
Travelling Expenses ...				182	11	5			
							3,486	1	9
„ RENT, INSURANCE, LIGHTING, AND FIRING (at 92, Victoria Street) ...							725	10	8
„ SINKING FUND PREMIUM...							183	6	8
„ PUBLICATIONS :—									
Journal ...				1,540	15	2			
"Science Abstracts"—									
Disbursements ...	£1,820	5	8						
Less Receipts ...	1,319	12	2						
				500	13	6			
							2,041	8	8
„ MEETINGS :—									
Advance Proofs, Refreshments, etc. ...				157	17	3			
Reporting				55	13	0			
							213	10	3
„ LOCAL SECTIONS ...							578	17	7
„ PREMIUMS ...							127	6	9
„ BRITISH ELECTROTECHNICAL COMMITTEE ...							244	10	6
„ CONVERSAZIONE ...							242	14	6
„ ANNUAL DINNER ...							60	19	3
„ DEPRECIATION :—									
Library (10 %) ...				168	18	3			
Furniture (5 %) ...				20	13	4			
							189	11	7
„ MISCELLANEOUS EXPENSES ...							140	17	4
„ BALANCE carried to General Fund ...							3,283	3	11
							£11,517	19	5

Electrical Engineers.

EXPENDITURE FOR THE YEAR DECEMBER, 1909.

Cr.

INCOME.

	£	s.	d.	£	s.	d.
By Subscriptions				10,558	0	6
„ Dividends on Investments :—						
Life Compositions Fund	£144	13	9			
General and Entrance Fees Funds	109	18	4			
				254	12	1
„ Interest				6	2	9
„ Journal :—						
Sales	209	13	10			
Advertisements	472	0	0			
				681	13	10
„ Wiring Rules				10	6	8
„ Model General Conditions for Contracts				7	3	7
				£11,517	19	5

BALANCE SHEET,

Dr.

LIABILITIES.

	£	s.	d.	£	s.	d.
To Salomons Scholarship Trust Fund (Income)				18	16	4
„ David Hughes Scholarship Trust Fund:—						
Capital uninvested	1	5	0			
Income	36	7	6			
				37	12	6
„ Wilde Benevolent Trust Fund (Income)...				165	11	8
„ Life Compositions Fund				5,613	3	0
„ Building Fund				39,189	10	6
„ Kelvin Lecture Fund:—						
Capital	862	10	10			
Income	25	0	0			
				887	10	10
„ Sundry Creditors				2,550	19	8
„ Economic Life Assurance Society				26,000	0	0
„ Reserve for Redemption of Cost of Building ...				183	6	8
„ Local Sections:—						
Due to Hon. Sec. Birmingham Section				10	5	5
„ Subscriptions received in advance				75	0	0
„ Foreign Visit Fund				39	10	0
„ General Fund				10,135	10	8
				£84,906	17	3

ROBERT HAMMOND,
Honorary Treasurer.

P. F. ROWELL,
Secretary.

We beg to report that we have audited the Balance Sheet of the Institu-
together with the annexed Statements of Account. We have obtained all the
Bankers' Certificates of Investments and the Title Deeds of the Tothill
Sheet is properly drawn up so as to exhibit a true and correct view of the
and the explanations given to us and as shown by the books of the

ALLEN, BIGGS & CO.,
Chartered Accountants,
147, Leadenhall Street, E.C.

April 20, 1910.

31st DECEMBER, 1909.

Cr.

ASSETS.

		£	s.	d.	£	s.	d.
By General Fund Investments	(at cost)				3,270	10	1
,, Kelvin Lecture Fund Investments	,, ...				862	10	10
,, Tothill Street Buildings and Site	,, ...				19,260	17	1
,, Institution Building and Lease ...	,, ...				57,124	2	4
,, Sundry Debtors					1,398	8	2
,, Local Sections :—							
Cash in hands of Hon. Sec. Dublin Section		9	19	9			
do. do. do. Glasgow do.		15	3	2			
do. do. do. Manchester do.		8	0	3			
do. do. do. Newcastle do.		9	16	8			
do. do. do. Yorkshire do.		9	15	6			
					52	15	4
,, Library					1,520	4	1
,, Vellum Diploma Forms					2	5	9
,, Furniture					392	13	6
,, Sinking Fund, Premium Paid					183	6	8
,, Cash :—At Bankers'		596	17	2			
Petty Cash		76	14	7			
P.O. Savings Bank (Wilde Benevolent Trust Fund Income)		165	11	8			
					839	3	5
					£84,906	17	3

tion of Electrical Engineers, dated 31st December, 1909, and above set forth, information and explanations we have required. We have inspected the Street Property. In our opinion the Statements are correct, and the Balance state of the Institution's affairs according to the best of our information Institution.

H. ALABASTER,
SIDNEY SHARP, } *Honorary Auditors.*

Dr.

	£	s.	d.	£	s.	d.
To Excesses of Income over Expenditure to Dec. 31, 1908 ...				33,352	8	11
Add Excess of Income over Expenditure for 1909				3,283	3	11
				36,635	12	10
Less Transfers (as per last Account) :—						
To Building Fund	25,637	11	4			
To Kelvin Lecture Fund	862	10	10			
				26,500	2	2
				£10,135	10	8

Cr.

		£ s. d.	£ s. d.
By Investments (at cost) :—			
£623 Great Western Railway 5% Preference Stock		999 18 1	
£2,600 Natal Zululand Railways 3% Debentures		2,270 12 0	
			3,270 10 1
„ Balance made up as follows :—			
ASSETS.			
Sundry Debtors	1,398 8 2		
Cash in Hand	891 18 9		
Furniture	392 13 6		
Library	1,520 4 1		
Vellum Diploma Forms ...	2 5 9		
Sinking Fund	183 6 8		
Due from Building Fund...	5,582 5 11		
		9,971 2 10	
LIABILITIES.			
Uninvested Balances of Special Funds	286 10 6		
Sundry Creditors	2,561 5 1		
Subscriptions in Advance	75 0 0		
Reserve for Redemption of Cost of Building ...	183 6 8		
		3,106 2 3	
			6,865 0 7
			£10,135 10 8

Dr.

	£	s.	d.	£	s.	d.
To Amount (as per last Account)				35,753	14	6
" " transferred from Entrance Fees Fund				2,201	8	7
" Dividends on Investments				392	14	0
" Revenue from Tothill Street Property				668	5	7
" Subscriptions and Donations				171	13	2
" Surplus from Vellum Diplomas				1	14	8
				39,189	10	6
" Balance made up as follows :—						
Mortgage from Economic Life Assurance Society	26,000	0	0			
Due to Life Compositions Fund	5,613	3	0			
Due to General Fund	5,582	5	11			
				37,195	8	11
				£76,384	19	5

FUND.

Cr.

	£ s. d.	£ s. d.	£ s. d.
By Tothill Street Buildings and Site (as per last Account)...			19,260 17 1
" Institution Building and Lease :—			
(*a*) Outlays thereon :—			
Purchase Money	50,000 0 0		
" Expenses ...	544 19 0		
Structural Alterations to December 31, 1909 ...	3,454 9 3		
		53,999 8 3	
(*b*) Expenses during Structural Alterations :—			
Ground Rent	1,239 11 6		
Rates and Taxes	589 3 1		
Repairs	4 15 0		
Insurance	73 10 0		
Mortgage Interest	644 16 9		
	2,551 16 4		
Less Rent from Tenants ...	1,786 9 10		
		765 6 6	
(*c*) Mortgage Expenses		443 10 6	
(*d*) Loss on Sale of Securities		1,915 17 1	
			57,124 2 4
			£76,384 19 5

LIFE COMPOSITIONS

Dr.

	£	s.	d.
To Amount (as per last Account)	5,581	13	0
„ Life Composition received in 1909	31	10	0
	£5,613	3	0

ENTRANCE FEES

Dr.

	£	s.	d.
To Entrance Fees from 1902 to 1908—			
(As per last Account)	5,156	19	6
„ Entrance Fees received in 1909	764	2	0
	£5,921	1	6

FUND.

Cr.

	£	s.	d.
By Balance (due from Building Fund)	5,613	3	0
	£5,613	3	0

FUND.

Cr.

	£	s.	d.
By Building Fund :—			
Amounts transferred (as per last Account)	3,719	12	11
Amount transferred in 1909	2,201	8	7
	£5,921	1	6

KELVIN LECTURE

Dr.

	£	s.	d.
To Amount (as per last Account)	862	10	10
„ Dividends	25	0	0
	£887	10	10

LIBRARY.

Dr.

	£	s.	d.
To Amount (as per Balance Sheet)	1,520	4	1
	£1,520	4	1

Cr.

	£	s.	d.
By Investment (at cost):—			
£1,000 2½% Consolidated Stock	862	10	10
„ Balance Uninvested	25	0	0
	£887	10	10

LIBRARY.

Cr.

	£	s.	d.
By Outlays on Books, Pictures, etc., to December 31, 1908 ...	2,377	2	2
Less Provision for Depreciation (1901–8)	819	7	3
As per last Balance Sheet	1,557	14	11
„ Expenditure on Books and Binding in 1909	131	7	5
	1,689	2	4
Less 10% Depreciation for 1909	168	18	3
	£1,520	4	1

SALOMONS SCHOLARSHIP

Dr.

	£	s.	d.
To Amount (as per last Account)	2,126	19	3
	£2,126	19	3

SALOMONS SCHOLARSHIP

Dr.

	£	s.	d.
To Amount paid to Scholars in 1909...	75	0	0
„ Balance carried to Balance Sheet	18	16	4
	£93	16	4

DAVID HUGHES SCHOLARSHIP

Dr.

	£	s.	d.
To Amount (as per last Account)	2,000	0	0
	£2,000	0	0

DAVID HUGHES SCHOLARSHIP

Dr.

	£	s.	d.
To Amount paid to Scholars in 1909...	50	0	0
„ Balance carried to Balance Sheet	36	7	6
	£86	7	6

WILDE BENEVOLENT

Dr.

	£	s.	d.
To Amount (as per last Account)	1,744	16	0
	£1,744	16	0

WILDE BENEVOLENT

Dr.

	£	s.	d.
To Grant made in 1909	25	0	0
„ Balance carried to Balance Sheet	165	11	8
	£190	11	8

TRUST FUND.

	Cr. £	s.	d.
By Investments (at cost) :—			
£1,500 New South Wales 3½ % Stock	1,556	5	9
£500 Cape of Good Hope 3½ % Stock	570	13	6
	£2,126	19	3

TRUST FUND (Income).

	Cr. £	s.	d.
By Balance (as per last Account)	23	19	2
„ Dividends received in 1909	69	17	2
	£93	16	4

TRUST FUND.

	Cr. £	s.	d.
By Investment (at cost).:—£2,045 Staines Reservoirs 3 % Guaranteed Debenture Stock	1,998	15	0
„ Balance carried to Balance Sheet	1	5	0
	£2,000	0	0

TRUST FUND (Income).

	Cr. £	s.	d.
By Balance (as per last Account)	25	0	7
„ Dividends received in 1909	61	6	11
	£86	7	6

TRUST FUND.

	Cr. £	s.	d.
By Investments (at cost):—			
£875 Great Eastern Railway Metropolitan 5 % Guaranteed Stock	1,493	16	3
£215 North Eastern Railway 4 % Guaranteed Stock ...	250	19	9
	£1,744	16	0

TRUST FUND (Income).

	Cr. £	s.	d.
By Balance (as per last Account)	134	15	4
„ Dividends received in 1909	52	7	0
„ Interest do. do.	3	9	4
	£190	11	8

The Institution of

Statement of Accounts

Dr. CAPITAL

	£	s.	d.
To Balance as per last Account	3,000	0	0
„ Transfer from Income	500	0	0
	£3,500	0	0

Dr. INCOME AND

	£	s.	d.
To Balance as per last Account	524	3	9
„ Dividends on Investments...	101	17	4
„ Interest on Deposit	3	16	4
„ Donations under £5	6	15	6
„ Donations of £5 and over	42	6	6
„ Annual Subscriptions	105	1	0
	£784	0	5

Dr. BALANCE

	£	s.	d.
To Capital	3,500	0	0
„ Income and Expenditure Account	203	15	11
	£3,703	15	11

We have examined the above Accounts with the Receipt Book, Cash Book, and we find them to be correct.

April 19, 1910.

LENT FUND OF

Electrical Engineers.

to December 31, 1909.

ACCOUNT.

Cr.

	£	s.	d.
By Balance carried to Balance Sheet, viz.:—			
Investments—			
£961 7s. 7d. Cape of Good Hope 3% Stock	950	0	0
£593 1s. 7d. New South Wales 3% Stock	600	0	0
£420 Great Eastern Railway 4% Pref. Stock...	503	18	3
£600 North Staffordshire Railway 3% Deb. Stock	551	0	9
£750 East Indian Railway 3½% Deb. Stock	737	18	0
Cash	157	3	0
	£3,500	0	0

EXPENDITURE ACCOUNT.

Cr.

	£	s.	d.
By Grants	77	0	0
„ Postages, Printing, &c.	3	4	6
„ Transfer to Capital...	500	0	0
„ Balance carried to Balance Sheet, viz. :—			
Cash	203	15	11
	£784	0	5

SHEET.

Cr.

				£	s.	d.
By Investments (Capital Account)—						
£961 7s. 7d. Cape of Good Hope 3% Stock				950	0	0
£593 1s. 7d. New South Wales 3% Stock				600	0	0
£420 Great Eastern Railway 4% Pref. Stock				503	18	3
£600 North Staffordshire Railway 3% Deb. Stock				551	0	9
£750 East Indian Railway 3½% Deb. Stock				737	18	0
				3,342	17	0
„ Cash—						
At Bankers'	£358	16	5			
Petty Cash	2	2	6			
				360	18	11
				£3,703	15	11

Bankers' Pass Book, and Vouchers, also Bankers' Certificate of Investments,

H. ALABASTER, SIDNEY SHARP, } *Honorary Auditors.*

The CHAIRMAN: There is one matter not mentioned in the report to which I should like to refer, and that is the Museum. I should like to see members coming forward with anything they wish to present to our Museum, because in our new premises we shall have plenty of room to accommodate those articles.

Mr. Hammond informs me that he would rather deal with the financial part of the report on the motion for the adoption of the accounts, and I will therefore now simply formally move the adoption of the report of the Council; if any members present have any observations to make on the report we shall be very glad to hear them after the motion has been seconded.

Mr. R. K. GRAY: I have very much pleasure in seconding the motion.

The CHAIRMAN: If no member has any remark to make I will put the motion: "That the report of the Council be received and adopted."

The resolution was put and carried unanimously.

The CHAIRMAN, having read the Auditors' Certificate, called upon Mr. Hammond to present the Financial Statement for the year 1909.

Mr. ROBERT HAMMOND: It gives me much pleasure to move: "That the Statement of Accounts and Balance Sheet for the year ended December 31, 1909, as presented, be received and adopted." I should like to draw your attention to one or two points in the Accounts. In the first place you will, I am sure, be glad to see that in spite of hard times we have actually carried forward a profit, if I may so term it, of £3,283 3s. 11d. You will notice that on one side of the Balance Sheet it is stated that our assets amount to £84,906, while on the other side, among the liabilities, there are some items which represent debts, and others which represent accumulations that are not debts. Deducting the actual debts, including the recent mortgage of £26,000 from the assets, we have to the good the sum of £55,825; so that if from any cause this Institution had to realise its property it would have £55,825 in hand. Among the assets I will draw your attention to one amount which stands out, namely, the building and the lease. Of course the £55,825 does not exist in the form of banknotes, as it is almost entirely locked up in our new Institution building. I wish also to draw your attention to the Sinking Fund premium paid, £183 6s. 8d., which comes into the Accounts as a reserve for the redemption of the cost of the building. The Council felt that in purchasing the lease of a building, which lease would expire in about seventy-five years, it was their duty to provide an annual sum by means of which the £50,000 that was paid for the lease would be entirely wiped off. Of course it may be said that as we have so much to the good there is no need to do so, but the Council took a prudent view of the matter and took out in an Insurance Company a Sinking Fund policy by which the payment of an annual premium of £183 6s. 8d. for seventy-five years ensures at the end of that period a sum of £50,000, the amount paid for the lease of the building. When the lease falls in we shall be in identically the same position financially as we were on the day when we handed over to the

Medical Colleges £50,000 to cover the purchase. We, however, have passed a resolution to increase that £50,000 provision by making provision for a further sum of £25,000, so that the total amount which we shall receive at the end of the period will be £75,000. This will not only cover the cost of the lease, but also any expenditure that in the meantime we may make upon the building. I also draw your attention to the item of £26,000 received from the Economic Life Assurance Society. We made a favourable arrangement with that Society for this loan, and we have also arranged with regard to it to pay out of revenue annually a sum which will redeem the loan entirely at the end of twenty-five years. Our investments have had a rude shock in consequence of the necessary realisations for purchasing the lease of the Institution building, and are now reduced to the modest amount of £4,133, £862 of which is allocated to the Kelvin Lecture Fund. The General Fund now stands at a credit amount of £10,135. The Building Fund stands at £76,384, a very large increase upon the amount at which it stood twelve months ago. It has been increased during the year by a transfer from the Entrance Fees Fund of £2,201, also by subscriptions, dividends on investments, and revenue from the Tothill Street property amounting to £1,234; and we have also included the mortgage and the Life Compositions Fund, as we have borrowed the £5,613 standing to its credit—I trust only temporarily—and we have also borrowed from the General Fund £5,582. These amounts have been borrowed from these funds with the idea that very shortly donations to the Building Fund may enable us to pay ourselves back. It gives me much pleasure to move the resolution which stands in my name.

Mr. R. K. Gray: I have much pleasure in seconding the resolution for the adoption of the Accounts. Mr. Hammond has, as he always does, given such a clear statement with regard to the Accounts that I need not add anything, but I would like to take this opportunity to tell you all that the Institution is very much indebted indeed to Mr. Hammond for the large amount of hard work he puts into looking after our interests. I can assure you, as Chairman of the Finance Committee, that the position of Honorary Treasurer of the Institution of Electrical Engineers, especially for the last year or two, has not been at all a sinecure. I formally second the Accounts, and I am sure that you quite agree with all the remarks I have made with regard to our friend, Mr. Hammond.

The Chairman: The resolution has been duly proposed and seconded. I will now ask if any members have any observation to make or any questions to ask. The Accounts are open for discussion.

If there are no observations or remarks, I will put the motion: "That the Statement of Accounts presented by the Honorary Treasurer be received and adopted."

The resolution was put, and carried unanimously.

Mr. W. M. Mordey: I am very glad it falls to my lot to-night to move a resolution of our thanks to the two institutions to which we

owe so much for their hospitality and kindness—the Institution of Civil Engineers and the Royal Society of Arts. It will seem strange to us at our annual meetings when we no longer have to express our thanks for the hospitality which for thirty-eight years has been extended to us by the Institution of Civil Engineers, but I am sure that any feeling we have to-night of gratitude to the Institution of Civil Engineers will have in it no savour at all of relief. We have never felt, in proposing this vote of thanks to the Institution of Civil Engineers for their kindness to us in giving us the use of their hall, that they in any way grudged what they had done for us. In going into our own building, we can only hope that we, in our turn, may be able to do something in the same broad-spirited manner to foster other engineering and scientific interests that may need support. We have had to-night another example of the many things for which we have to thank the Institution of Civil Engineers. You, Sir, have referred to our adoption of the regulations as to professional conduct that have recently been issued by that institution, and have, in fact, been incorporated in its constitution. When the Council considered the matter, it was found that the Institution of Civil Engineers had done the work so well that we could not improve on their rules, which, by permission, were therefore adopted in their entirety. I am sure you will all agree with me when I say that there was a very great deal to be said in favour of our taking that course and so working in parallel on that important subject of professional conduct with the parent institution. I now beg formally to move: "That the best thanks of the Institution be, and are hereby accorded, to the Council of the Institution of Civil Engineers and to the Council of the Royal Society of Arts for the great courtesy extended to the Institution in placing their rooms at its disposal for the holding of its general meetings." Although we are all very glad indeed to have our own home, I am sure we shall all experience a feeling of regret in realising that this is the last time that we shall have the pleasure of passing this resolution.

Mr. W. R. Cooper: I have much pleasure in seconding that resolution.

The resolution was then put and carried unanimously.

Major W. A. J. O'Meara, C.M.G.: There are a certain number of active members of this Institution who devote a considerable amount of their time to the promotion of our best interests, and, I think, help Mr. Hammond in presenting such a favourable report, because they collect funds for us in foreign countries. I therefore have much pleasure in proposing: "That the best thanks of the Institution are given to the Local Honorary Secretaries and Treasurers abroad for their kind services during the past year."

Mr. H. M. Sayers: I have much pleasure in seconding this motion. Those of us who have lived abroad know the tendency there is to feel isolated and out in the world, out of touch with one's fellow members; and to have these personal nuclei as Secretaries and Treasurers, if they are only within mail reach, is a very great help towards keeping up the

feeling of camaraderie and comradeship that should exist between us all.

The resolution was put and carried with acclamation.

Mr. J. F. C. SNELL: After the remarks which have fallen from Mr. Gray, with which you have already shown your entire sympathy, it is only necessary for me to propose this resolution in very brief terms, because I am sure you will pass it with acclamation: "That the best thanks of the Institution be given to Mr. Robert Hammond in recognition of the valuable services rendered by him as Honorary Treasurer of the Institution during the past session."

Mr. J. T. MORRIS: I have much pleasure in seconding the resolution. Those of us who have acted as honorary treasurers to various societies know what an amount of time has to be devoted to such work, and in an institution of this magnitude the work must be very large indeed. I have very much pleasure in seconding the motion.

The resolution was carried by acclamation.

Mr. R. HAMMOND: Mr. Chairman and Gentlemen, I need hardly say that it gives me very great pleasure to acknowledge the very kind way in which my services appear to be appreciated. I am very gratified indeed to find on the part of the members of the Institution such an appreciation of the little work which I am able to do.

Mr. H. HUMAN: We have heard a good deal about money this evening, and you will have gathered from the report that we have been expending a good deal lately, and in the right direction. Consequently our accounts are swollen, and that means that the labours of our honorary auditors have grown proportionately, and I feel sure that you will accord them a very hearty vote of thanks for the services they have rendered to us. Let me remind you that those services are very responsible, and that they are carried out in a most conscientious manner. I have therefore great pleasure in moving: "That the best thanks of the Institution be accorded to the Honorary Auditors, Mr. Sidney Sharp and Mr. H. Alabaster, for their kind services during the past year."

Mr. W. B. ESSON: I have great pleasure in seconding the resolution.

The resolution was put and carried unanimously.

Mr. S. Z. DE FERRANTI: I have much pleasure in proposing: "That the best thanks of the Institution be tendered to Messrs. Bristows, Cooke and Carpmael for their kind services in their capacity of Honorary Solicitors to the Institution during the past year."

Mr. F. POOLEY: I have much pleasure in seconding the resolution.

The resolution was put and carried unanimously.

Mr. J. W. SPARSHATT: As representing Messrs. Bristows, Cooke and Carpmael I thank you very much for the vote of thanks which you have passed to the firm. It is always a pleasure to all of us in the firm to do any work for the Institution, and so far as the officers of the Institution are concerned I know it is appreciated, and we get all the help possible from them.

The CHAIRMAN: I have to report with regard to the Offices of President, Vice-President, Associate Members of Council, Honorary Treasurer and Honorary Auditor, that no nominations having been received for these offices other than those announced at the Ordinary General Meeting of April 21, 1910, the Council's nominees are in accordance with Article 45 of the Articles of Association duly elected to their respective offices.

The scrutineers have not yet counted all the ballot papers, and I am therefore unable to announce yet the result of the ballot for the election of Members of Council.

I suggest, therefore, to save time that we adjourn the Annual General Meeting now, that we take the Special General Meeting of the Institution, and that we resume the business of the Annual General Meeting when we have the report of the scrutineers of the ballot before us.

The motion having been agreed to, the meeting was adjourned, and resumed after an interval of 15 minutes.

The CHAIRMAN: I have been handed by the Scrutineers the following Report of the result of the voting for the election of five Members of Council:—

P. V. McMahon	854 votes.
S. L. Pearce	852 „
H. Dickinson	846 „
R. K. Morcom	842 „
H. Faraday Proctor...	696 „
J. E. Kingsbury	438 „

I accordingly declare Messrs. Dickinson, McMahon, Morcom, Pearce, and Proctor to be the five elected Members of the Council.

The following will therefore constitute the Council for the Session 1910–11:—

President.

S. Z. DE FERRANTI.

Vice-Presidents.

W. DUDDELL, F.R.S.
S. EVERSHED.
W. H. PATCHELL.
J. H. RIDER.

Members of Council.

W. W. COOK.
H. DICKINSON.
G. K. B. ELPHINSTONE.
W. JUDD.
P. V. MCMAHON.
T. MATHER, F.R.S.
R. K. MORCOM.
W. M. MORRISON.
MAJOR W. A. J. O'MEARA, C.M.G.
S. L. PEARCE.
H. FARADAY PROCTOR.
J. F. C. SNELL.
G. STONEY, B.A.
C. H. WORDINGHAM.
A. H. WALTON.

Associate Members of Council.

E. RUSSELL CLARKE. | S. MORSE.
J. E. TAYLOR.

Honorary Treasurer.

ROBERT HAMMOND.

Honorary Auditors.

H. ALABASTER. | SIDNEY SHARP.

I think we ought to pass a hearty vote of thanks to the scrutineers for their work. They have been nearly an hour and a half in counting the votes on more than a thousand papers. It has been a very laborious task, and I am sure we are very thankful to them for the trouble they have taken in the matter.

The resolution was carried by acclamation.

The meeting adjourned at 9.35 p.m.

A Special General Meeting of Members, Associate Members, and Associates duly convened, and held at the Royal Society of Arts, John Street, Adelphi, W.C., on Thursday evening, May 26, 1910—Mr. W. DUDDELL, F.R.S., Vice-President, in the chair.

The SECRETARY read the Notice convening the meeting.

The CHAIRMAN : I will now call upon Mr. Hammond to explain the object of the resolution.

Mr. HAMMOND : When the Council saw that they could purchase the lease of the Institution building for £50,000 and that not more than £20,000 would be required to do all that was wanted you were asked to sanction that expenditure, first of £50,000 and then of £20,000. When later the accounts were made up, it was decided to treat the mortgage expenses, the loss on the sale of securities, and the outlays during structural alterations, such as ground rent, rates, etc., as part of the capital expenses of the building. These items were accordingly brought into the Building Fund as a debit and so caused the expenditure to be more than the £70,000. It may also be necessary at some future time for the purpose of letting to arrange as suites of offices that part of the building not required by the Institution. To cover such expenditure, and the outlays to which I have just referred, the members are asked to sanction in one resolution a sum beyond what is deemed will actually be necessary, but which will obviate for ever, it is hoped, the inconvenience that might arise of having these special meetings.

The CHAIRMAN : I will now formally move :—

"That, in addition to the sum of £20,000 authorised by Special Resolution of the 29th of July, 1909, to be expended, a further expenditure of a sum not exceeding £10,000 in connection with the Institution Building on (*a*) structural alterations, furniture and fittings, and (*b*) outlays during present or future structural alterations, including ground rent, rates, and taxes, less rents received or to be received from tenants in the Building, be sanctioned and approved, and that the Council be authorised to make such financial arrangements (including the borrowing of money on the security of the Institution Building and on the Institution property in Tothill Street) as the Council may consider necessary for the above purpose."

Mr. R. K. GRAY: I have very much pleasure in seconding the resolution. As Mr. Hammond has explained to you, the reason for the resolution is the following: We found ourselves about £1,170 short; and as there is a probability that our tenants for the part of the building which we do not require will move to their new quarters at the expiry of their agreement with us, two years hence, it was felt prudent, as there would be certain structural alterations to make if we wished to have fresh tenants to replace those that left us; first of all to make the full body of members acquainted with that fact so that there would be no misunderstanding, and, secondly, to ask them to authorise us to find the money that would be necessary to pay for the structural alterations; also to pay the charges and ground rent, as nothing can be earned during the year while the necessary structural alterations are in progress. We thought that by having this extra vote of £10,000 it would amply cover every expense that the Institution will have to make. We did not care about asking for £5,000, which might have been quite sufficient; we thought we had better make it £10,000, because, as Mr. Hammond has very properly said, estimates are estimates, and it does not do to be always calling Special Meetings of an Institution like this. We thought we had better do it at once, and I think if you gentlemen will accept this resolution you will be doing the best possible thing for the Institution.

The CHAIRMAN: The resolution is now open to discussion, and I invite any remarks on it.

Mr. W. B. ESSON: I should like to ask a question, if I may. Mr. Hammond told us nearly two years ago that £6,000 over and above the £50,000 for purchase of the building would be required to carry out the alterations that were contemplated. It was stated then that the estimated cost of the enlargement of the theatre, six months' rent of the old premises, removal, painting, new furniture, and new bookshelves, was £6,000. Accordingly our total liabilities in respect of capital were to be only £56,000. From £6,000 to £20,000 and finally to £30,000 is a very great jump, and I would like Mr. Hammond to give us some explanation of the extraordinary increase.

Mr. HAMMOND: Mr. Esson is correct in saying that when we acquired this building we did it upon the basis that we were going to spend £56,000, and that there would be no difficulty whatever in keeping our estimates within that £56,000. But when we found ourselves in possession of that building we felt as a Council that it would be wise to deal with it on a much broader basis. We felt, for instance, with regard to the theatre, that instead of making the very small alterations that we first deemed wise it would be better to make such drastic alterations, almost a rebuilding of the theatre, as to put us in the position of having a hall 30 per cent. bigger than the present hall of the Institution of Civil Engineers. We acknowledge that when we went into the undertaking originally we did so with the feeling that what was good enough for the colleges of physicians and surgeons would probably be good enough for us, and we put in £6,000 as

being certainly required for furniture and certain obvious structural alterations. But the Council on considering the matter came to the conclusion that the members would very much prefer that a first-class job were made of it, and that we should deal with it upon that basis. The members were accordingly called together, the facts were placed before them, and they sanctioned an expenditure of £70,000, up to which expenditure, therefore, we are fully justified.

Mr. Esson : I did not say you are not justified. I asked for explanation.

Mr. Hammond : The Council still see their way to do all that was contemplated for about £70,000, but, as I have explained, when to the actual expenditure on the building is added the loss on the sale of securities, mortgage, expenses, etc., they being treated as capital sums, we get beyond the total of £70,000.

The Chairman : Are there any more questions ?

Mr. W. R. Cooper: May I ask if this £10,000 will be available for the present alterations now being made, or whether it will be earmarked for future alterations ?

Mr. Hammond : The £10,000 is an amount, a portion of which will be used to wipe off the £1,000 or £2,000, or whatever the excess over the £70,000 may be, but the whole of the £10,000 will not be raised immediately; we have no idea of doing that. But in the course of four or five years if we have to alter the letable portion of the building materially, as Mr. Gray said, we should use the balance of the money for that purpose. We have no intention of spending the whole of the £10,000 upon the building at the present time.

The Chairman : Are there any further questions or remarks to be made on this resolution ? If there are no other remarks I will put the resolution to the meeting.

The resolution was then put, and declared by the Chairman to be carried unanimously.

OBITUARY NOTICES.

SHELFORD BIDWELL, F.R.S., died on December 18, 1909, at the age of 62. He was born at Thetford, and was educated at Caius College, Cambridge. Called to the bar in 1875 at the age of 28, he eventually abandoned law for scientific research, for which his natural talents better fitted him. He was the author of numerous papers before this Institution, the Royal Society, and the Physical Society, and lectured on electrical subjects at the Royal Institution and other centres. In 1881 he was elected an Associate Member, and three years later was transferred to full Membership. He carried out numerous valuable researches in magnetism and physiological optics, but his greatest scientific work was the discovery, in 1881, of the change caused by light in the electrical resistance of selenium, on which were founded several methods of electrically transmitting pictures to a distance. He was elected a Fellow of the Royal Society in 1886, and was President of the Physical Society in 1897 and 1898. He was an Associate Member of Council of the Institution for the year 1883–4.

ALFRED ARTHUR CAHEN, B.Sc., who died on September 17, 1909, at the age of 30, was educated at the Central Technical College, South Kensington, and afterwards spent several years under the Marconi Wireless Telegraph Company in various parts of the Continent. He left the Marconi Company to take up an important position at Erith with Callender's Cable and Construction Company, but contracted a serious and painful illness, which proved fatal within a year. He became an Associate of the Institution in 1901, and an Associate Member in 1904.

MAJOR PHILIP CARDEW, R.E., died on May 17, 1910, from the after-effects of an operation. Born in 1851, he was educated at the Royal Military Academy, Woolwich, where at the age of 20 he took honours and was awarded the Pollock Gold Medal. In 1876 he was placed in charge of the Bermuda military telegraphs, and later held various posts in the Submarine Mining Service. In 1888 he was appointed electrical adviser to the Board of Trade, which position he resigned in 1899 to take up consulting work in partnership with Sir William Preece, K.C.B., and his sons. Both in this practice and under the Board of Trade he was the pioneer of considerable useful work, including the electrical equipment of the Admiralty Dockyards, and the formulating of regulations for power supply, and for safeguarding

underground pipes against electrolysis. He was a director of the Brighton Railway during the progress of their electrification work on the South London Line, and was also the author of many useful inventions and papers, one of which on "Electric Railways" was read before the Society of Arts in March, 1901. He was a Member of Council of the Institution from 1886 to 1891 and from 1899 to 1903, and a Vice-President from 1902 to 1903.

ALFRED COLSON was born at Newport (Mon.) and educated at King's College, London, being afterwards articled to his father, who was then one of the chief engineers to the London and South-Western Railway. In 1872 he went to Birmingham as assistant engineer to Mr. Charles Hunt, and was given sole charge of a local gas undertaking. In 1882 he was appointed gas engineer to the Leicester Corporation, which position he held up to the time of his death. When the Leicester Corporation in 1892 took up electric lighting he had charge of this undertaking in addition to his other duties, and showed great ability in managing the two lighting departments. He invented a cash-box for prepayment meters, and a simple and effective method of removing naphthalene from coal gas. He was elected a Member of the Institution in 1900. His death occurred on May 27, 1910, after an illness lasting several months.

JOHN WILLIAM FLETCHER was born on April 24, 1834. In the early fifties he joined the service of the Electric and International Telegraph Company, and, prior to the transfer of the telegraphs to the State, he was in charge of the Chester and Holyhead section. When the transfer took place, he was one of those who elected to enter the service of the Railway Company, and then continued in charge of the the North Wales district until the year 1876. At that time he was appointed Telegraph Superintendent of the Northern Section of the London and North-Western Railway Company; and some two years later he was appointed chief telegraph superintendent and engineer of that Company, which position he held until his retirement in June, 1903. In 1872 he joined the Society of Telegraph Engineers and, until his death, he was a member of this Institution. He was one of the earliest contributors to the *Journal*, having in the year 1873 written an Original Communication on "Lightning Protectors" (vol. ii. p. 296). He was also a member of the Conference of Railway Telegraph Superintendents and Engineers from its inception until his retirement, and was President of the Conference in 1892. He was the inventor and patentee of numerous and varied appliances for the economical and safe working of railways; and the efficient state of the electric telegraph system of the London and North-Western Railway Company is sufficient evidence of his skill and ability as telegraph engineer. He died on July 11, 1910.

JULES HENRI FREDAY GRAMACCINI died at Paris on January 12, 1910, aged 77 years. He was born in Algeria, and in 1857 entered

the service of the French Government Telegraphs at Marseilles, being later connected with the Submarine Telegraph Company, of London, in the working of the Channel cables. In 1870 he received an appointment at Marseilles under the Eastern Telegraph Company, afterwards becoming chief of the Government Central Bureau at Marseilles. He took part in duplicating the Franco-Algerian cables, and in maintaining communication during the siege of Paris in 1870. In 1897 he retired from the French Government service and became Paris agent to the Government for the West African and Direct Spanish Telegraph Companies, which he represented at the International Telegraph Conference in London in 1903. He received the Cross of Chevalier of the Legion of Honour for services rendered to the French Government. His connection with the Institution as Foreign Member dates from 1875.

OSWALD HAES died on October 25, 1909, at the age of 44. He went to Australia in 1890 as the representative of the Brush Electrical Engineering Company. In 1896 he became responsible for the installation of electric lighting on the steamship *Airlie*, and in 1899 negotiated the purchase of the existing undertakings by the Melbourne Electric Supply Company and the Melbourne City Council. He was the author of a paper before the Electrical Association of New South Wales on "Economy in Electric Supply Stations." He also installed the new lighting system at Sydney. He was founder of the New South Wales Electrical Association, of which he was President for some time. He was elected an Associate of the Institution in 1886, and was transferred to full membership in 1890.

MUSGRAVE HEAPHY died on January 29, 1910, at the age of 67, after several years of failing health. At the age of 18 he fought under Garibaldi in the campaign of 1860–61, and received two medals. On his return to England he went into practice as a civil engineer, but a few years later he was appointed technical officer of the Phœnix Fire Office, and on the introduction of electric lighting he prepared a careful report on the subject, followed soon after by the first edition of the well-known Phœnix Fire Office Rules, which were the first code of wiring rules for the prevention of fire risks in electric lighting. Mr. Heaphy was elected a Member in 1886.

LOUIS DU BUISSON HUGO was born in 1882 and educated at the Cape of Good Hope University and at Cambridge, where he took a high place in both parts of the Natural Sciences Tripos. In 1906 he was articled to Messrs. Clayton and Shuttleworth, of Lincoln, and was also demonstrator at the Cambridge Engineering Laboratory. In 1907 he was appointed head of the Department of Physics and Electrical Engineering at the Victoria Institute, Bombay. In this year also he was elected an Associate Member of the Institution. He died on February 24, 1910.

FRANCIS HASTINGS MEDHURST was born in Russia in 1871, and educated at Highgate School. He was originally trained for the Civil Service, but was afterwards articled to Messrs. Parsons, of Newcastle-on-Tyne, and later became a consulting engineer. In late years he took great interest in political matters, and was Unionist candidate for West Islington in 1900 and 1906, and for the Borough of Stafford in the General Election of 1910. He joined the Institution in 1892, and was transferred to full membership in 1894. He died on October 26, 1909.

HERBERT JOHN MILLS was born in 1878 and educated at Plymouth and Penge, and at the Croydon Polytechnic. He assisted in carrying out the electric lighting of Earl's Court Exhibition in 1897, and subsequently was with various firms, and in practice on his own account as lighting engineer. In 1908 he was appointed to the position of chief engineer for the lighting of the Franco-British Exhibition, which he carried out successfully, and in the following year was elected an Associate Member of the Institution. He died on March 1, 1910.

JAMES NICOLSON died at Berlin on October 27, 1909. He was for twenty-six years superintendent of the two cable companies at Buenos Aires, which were absorbed a few years ago by the Western Telegraphic Company, when Mr. Nicolson was retained as superintendent. He retired in 1908. He was the compiler of a well-known system of telegraph code signals. He had been connected with the Institution, first as Associate and then as Associate Member, for a period of thirty years.

JOHN OLDHAM died on May 19, 1910, after a very short illness. He had been in the telegraph service for fifty-seven years. Commencing at the age of 17, he worked for eleven years in England, and in 1864 went out to La Plata to superintend the laying of the cable between Buenos Aires and Montevideo. The cable was opened for service in 1866, and Mr. Oldham remained as manager to the Cable Company. On the absorption of the company by the Western Telegraph Company in 1903, Mr. Oldham was appointed general manager of the branch, and his project of laying a cable between Argentina and Great Britain *viâ* Ascension Island was commenced. His death unfortunately occurred a week before the date fixed for the opening of the cable. He had been a Member of the Institution since 1881. Mr. Oldham was Local Honorary Secretary and Treasurer of the Institution for Uruguay from 1886 to 1902.

LIONEL EUGENE RADCLIFFE was born in 1876, and educated at the Finsbury Technical College. On leaving, he was engaged in electrical work with several well-known firms, and in 1900 worked under the Mersey Dock and Harbour Board. In 1904 he went out to

Egypt as assistant engineer to the Alexandria and Ramleh Railway Company and the Société Anonyme des Tramways d'Alexandrie. He was elected an Associate Member of the Institution in 1907. He died on January 19, 1910.

CHARLES J. ROBERTSON was born in 1860, and educated at the Merchant Taylors' School, where he gained a scholarship at St. John's College, Oxford. He afterwards studied chemistry under Professor Armstrong, and electrical engineering under Professors Ayrton and Perry at Finsbury Technical College. His connection with the lamp-making industry commenced in 1881, when he joined the Anglo-American Brush Company, and was associated with Mr. St. John Lane-Fox, one of the pioneers of the lamp industry. After working with various lamp companies in London and on the Continent and devoting considerable time to research work, he formed the Robertson Incandescent Lamp Company at Brook Green, and was manager and technical director until the time of his death, which took place on October 11, 1909.

ARTHUR DENLEY SMITH was born in 1869, and educated at Giggleswick School, and was afterwards articled to Messrs. Smith & Co. and Messrs. Hugill Bros., both of Keighley. In 1891 he joined the Keighley Engineering Company, becoming in 1893 outside representative and director, and in 1894 managing director. Mr. Smith was elected an Associate Member in 1903, and his death occurred on February 2, 1910.

PERCIVAL STOREY died on April 1, 1910, after a very long illness. He was educated at Oundle School, and from 1880 to 1891 was with the Orchard Engineering Works, Oundle, becoming assistant manager. In 1891 he worked under the late Marquis of Salisbury, and in 1898 joined the London office of the Torquay electricity undertaking, from which he was appointed borough engineer of Torquay shortly afterwards. He was 45 years old at the time of his death, and was elected an Associate Member of the Institution in 1904.

SIR CHARLES TODD, K.C.M.G., F.R.S., was born at Islington in 1826, and on completing his education was appointed assistant at Cambridge Observatory. In 1848 he was made Assistant Astronomer at Greenwich Observatory, and in 1854 returned to Cambridge. In 1855 he was appointed to be Superintendent of Telegraphs and Government Astronomer for South Australia. In this capacity he completed in 1858 the connection of Melbourne and Adelaide by telegraph, and afterwards the Transcontinental line between Europe and America. He held the post in South Australia for fifty years, and for thirty-five years was also Postmaster-General of that colony. He joined the Institution in 1874. In 1893 he was created K.C.M.G.

He died on February 1, 1910. Sir Charles Todd was Local Honorary Secretary and Treasurer of the Institution for South Australia from 1881 to 1906.

A. A. WHITLOCK was for eleven years resident engineer at the County of London Station at Wandsworth, and before that was resident engineer of the Dover Electric Supply undertaking. He died on December 26, 1909. His early training was with the Brush Electrical Engineering Company, and he was elected an Associate Member of the Institution in 1893, being transferred to membership in 1900.

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EXPLANATION OF ABBREVIATIONS.

[P] signifies a reference to the general title or subject of a Paper.

[*p*] signifies a reference to a subject incidentally introduced into a Paper.

[D] signifies a reference to remarks made in a Discussion upon a Paper, of which the general title or subject is quoted.

[*d*] signifies a reference to remarks incidentally introduced into a Discussion on a Paper.

Note.—The lists of speakers in the Discussion upon any Paper will be found in the Table of Contents at the beginning of the volume.

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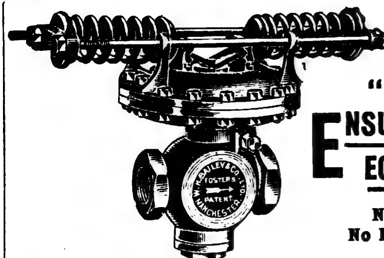

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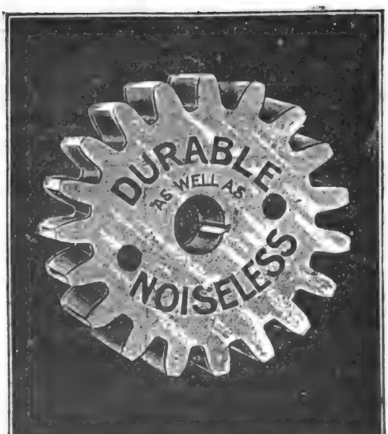

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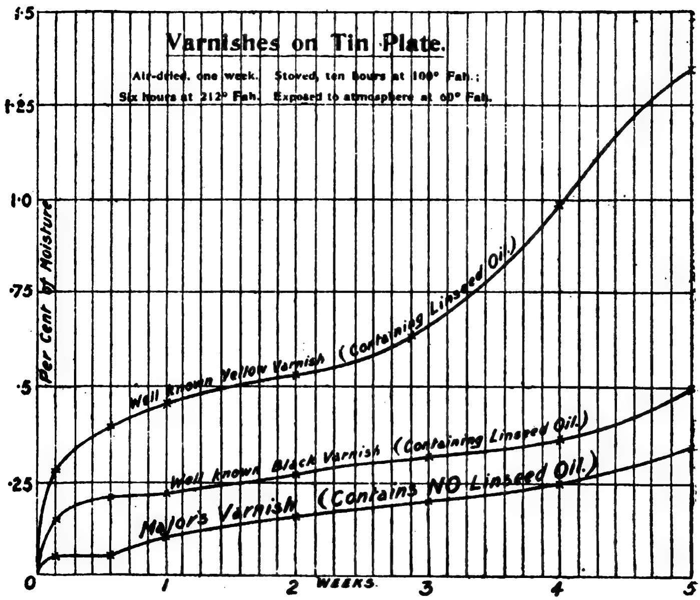

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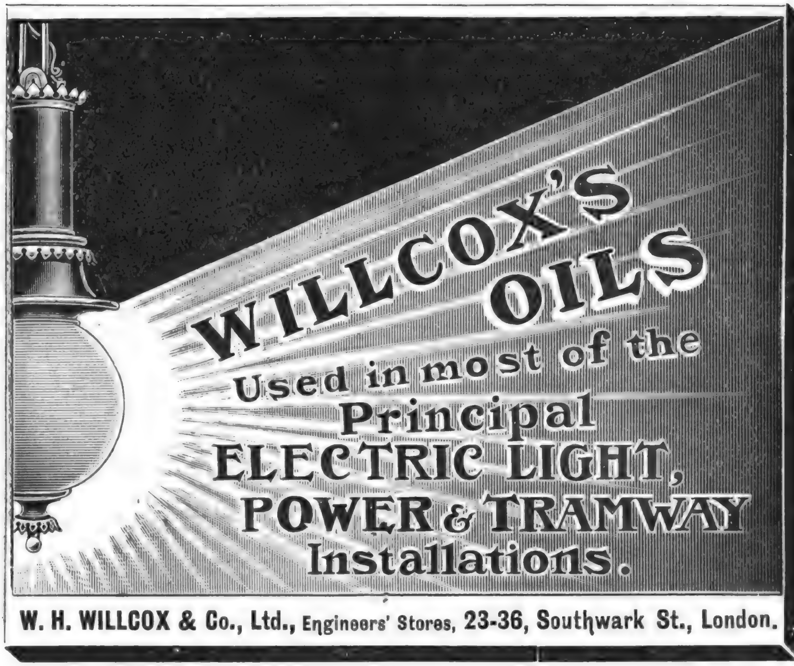

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